

# Progress in Top Quark Physics

Evelyn J Thomson

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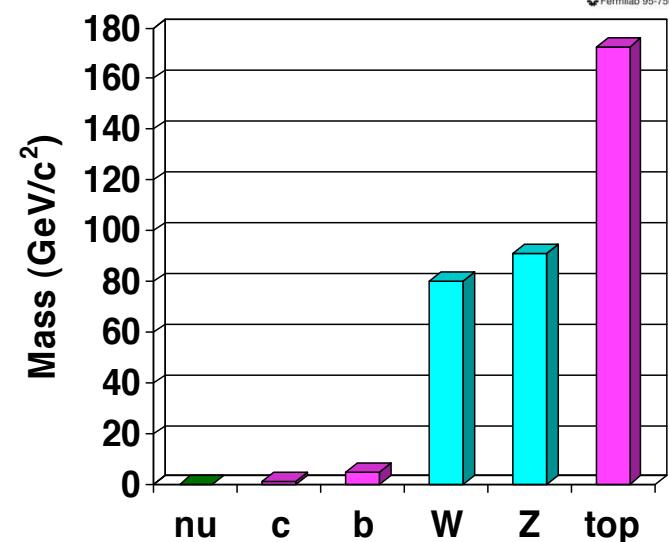
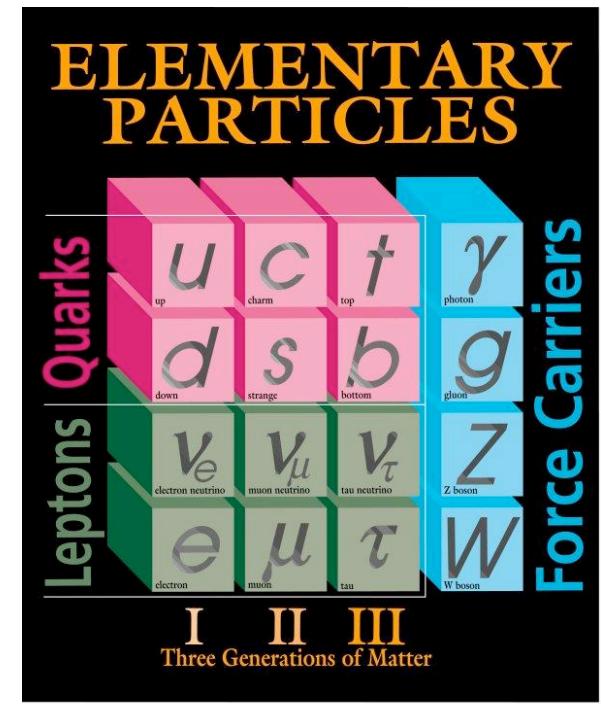
XVII Particles and Nuclei International Conference  
Plenary session 28 October 2005

CDF+D0 parallel session talks:

- V.4 Peter Renkel “*Top Quark Mass Measurement in Lepton+Jets Channel*”
- V.4 Tuula Maki “*Top Quark Mass Measurement in Dilepton Channel*”
- V.4 Robert Kehoe “*Top Quark Pair Production Cross Section Measurement*”
- V.4 Charles Plager “*Measurements of Top Quark Decay Properties*”
- V.4 Valentin Necula “*Search for Resonances in Top Quark Pair Production*”
- V.4 Yurii Maravin “*Search for Single Top Quark Production*”
- VI.2 Ben Kilminster “*Search for SM and MSSM Higgs Bosons*”

# Motivation

- **Most massive elementary particle**
  - Discovered in 1995 by CDF and D0
  - Only few dozen candidates in  $0.1 \text{ fb}^{-1}$
- **Is it really Standard Model top?  
Any effects from new physics?**
  - Only CDF and D0 can study top until LHC
  - Large  $1 \text{ fb}^{-1}$  data sample for Winter 2006
- **Top quark mass is a fundamental parameter in the Standard Model and beyond...**
  - Huge top quark mass induces significant radiative corrections to W boson mass
  - Reduced uncertainty on top quark mass imposes tighter constraints on unknowns, like Standard Model Higgs boson or SUSY
- **Significant background to many searches for new physics at LHC**

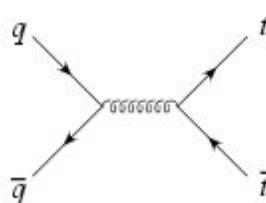


# Top Quark Production & Decay

Produce in pairs via strong interaction

Cacciari et al.  
JHEP 0404:068 (2004)  
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PRD 68 114014 (2003)

At  $\sqrt{s}=1.96$  TeV:  
85% qq  
15% gg

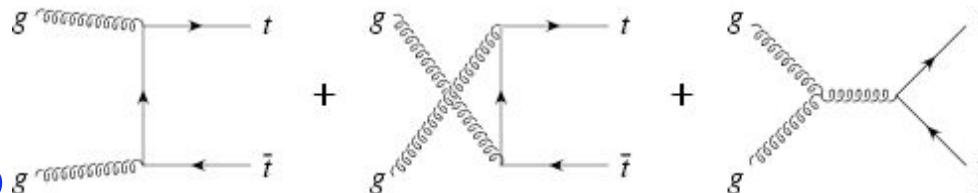


$m_t$ (GeV/c <sup>2</sup> )	$\sigma$ (pb)		
	Min	Central	Max
170	6.8	7.8	8.7
175	5.8	6.7	7.4

At  $\sqrt{s}=14$  TeV:

10% qq  
90% gg

$\sigma = 833 \pm 100$  pb

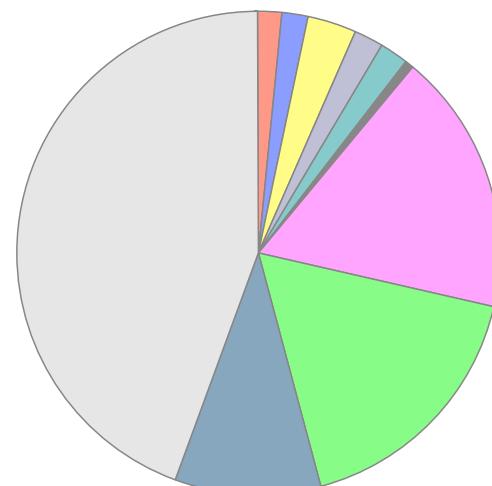


Decay singly via electroweak interaction  $t \rightarrow W^+ b$

$t \rightarrow W b$  has ~100% branching ratio  
Width ~1.5 GeV so lifetime  $10^{-25}$ s  
No top mesons or baryons!

Final state characterized by  
number and type of charged leptons  
from decay of  $W^+$  and  $W^-$  bosons

$t\bar{t} \rightarrow W^+ b W^- \bar{b}$  final states

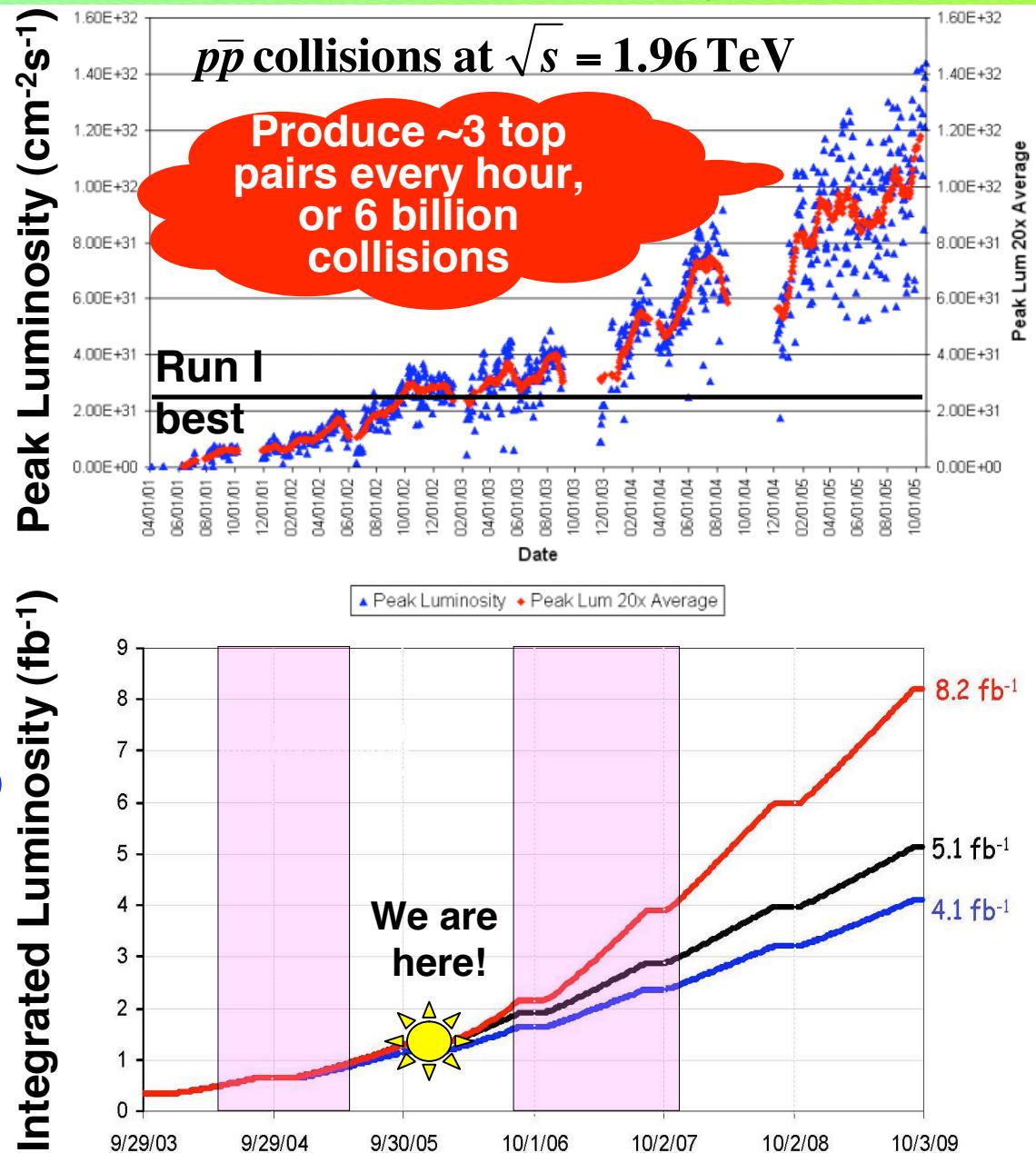


- ee Dilepton
- $\mu\mu$
- e $\mu$
- e $\tau$
- $\mu\tau$
- $\tau\tau$
- e+jets Lepton + jets
- $\mu+jets$
- $\tau+jets$
- all-hadronic

(Note  $e$  includes  $\tau \rightarrow e\bar{\nu}_e\nu_\tau$  and  $\mu$  includes  $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$ )

# Snapshot of Tevatron Operation

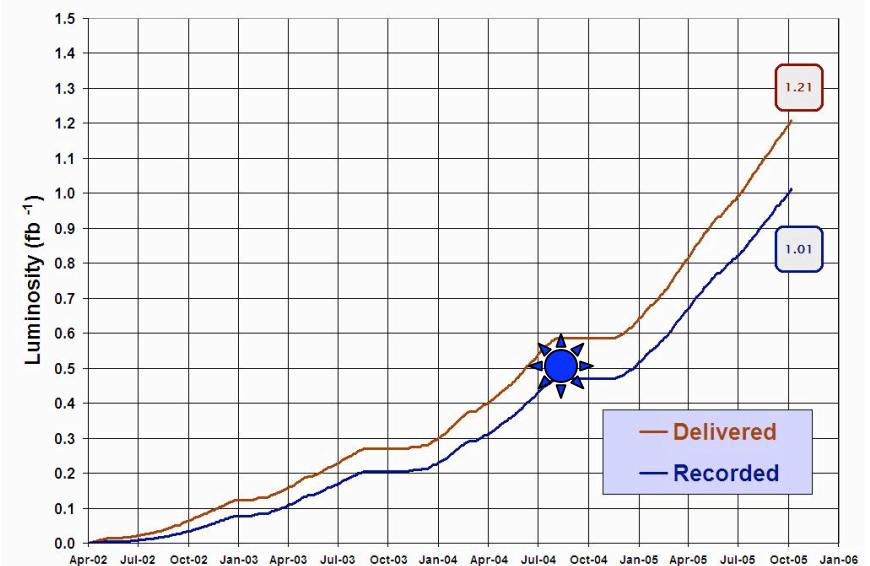
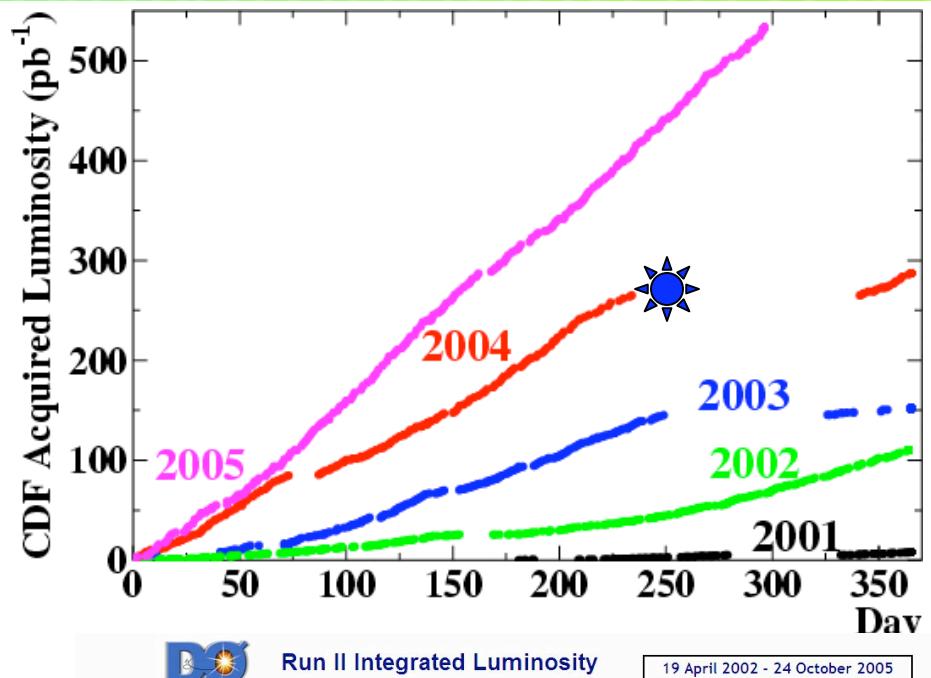
- World Record Peak Luminosity yesterday!
  - $1.58 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Deliver 8  $\text{fb}^{-1}$  if all upgrades succeed
  - Note electron cooling upgrade making good progress!
- Deliver 4  $\text{fb}^{-1}$  even if no further improvements
- Already delivered over  $1\text{fb}^{-1}$  to experiments



# Snapshot of CDF & DO Data

☀ Current top quark physics results from ~350 pb<sup>-1</sup> of data up to September 2004

- 2005 excellent year for CDF and D0!
- Both experiments have collected over 1 fb<sup>-1</sup> of data at  $\sqrt{s}=1.96$  TeV
- Watch out for top results with 1 fb<sup>-1</sup> at Moriond 2006

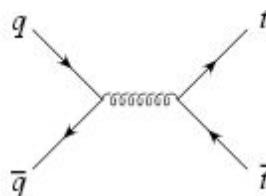


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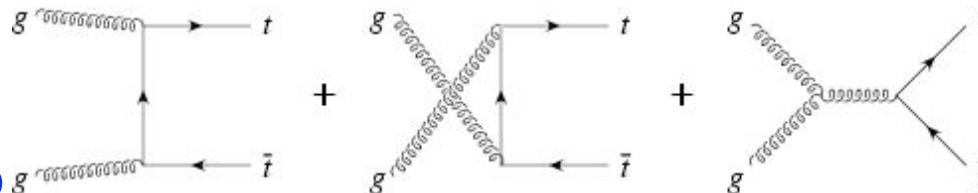


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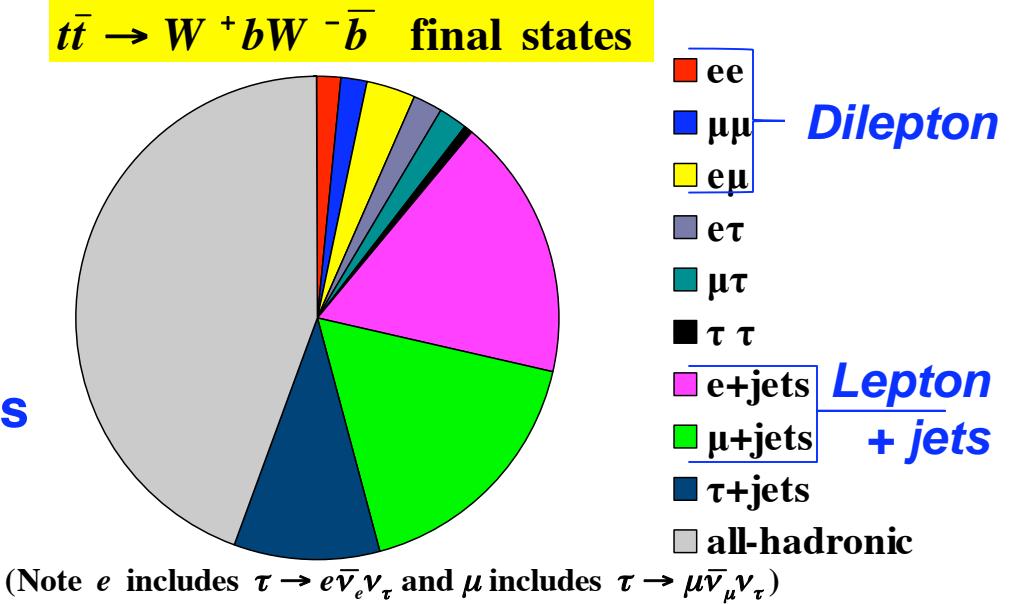
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# Dilepton

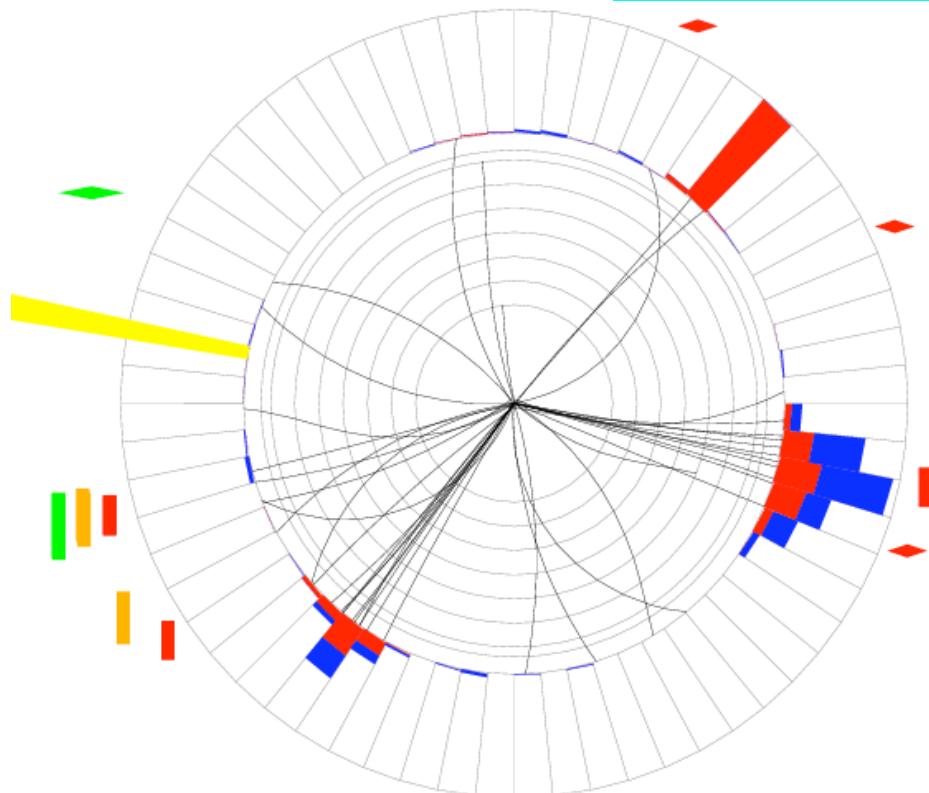
$$\sigma(t\bar{t}) = 8.6 \pm^{2.3}_{2.0} (\text{stat}) \pm^{1.2}_{1.0} (\text{syst}) \pm 0.6 (\text{lumi}) \text{ pb}$$

Events	ee	$\mu\mu$	e $\mu$	Total
Bkg	$1.0 \pm 0.3$	$1.3 \pm 0.4$	$4.5 \pm 2.2$	$6.8 \pm 2.2$
Data	5	2	21	28

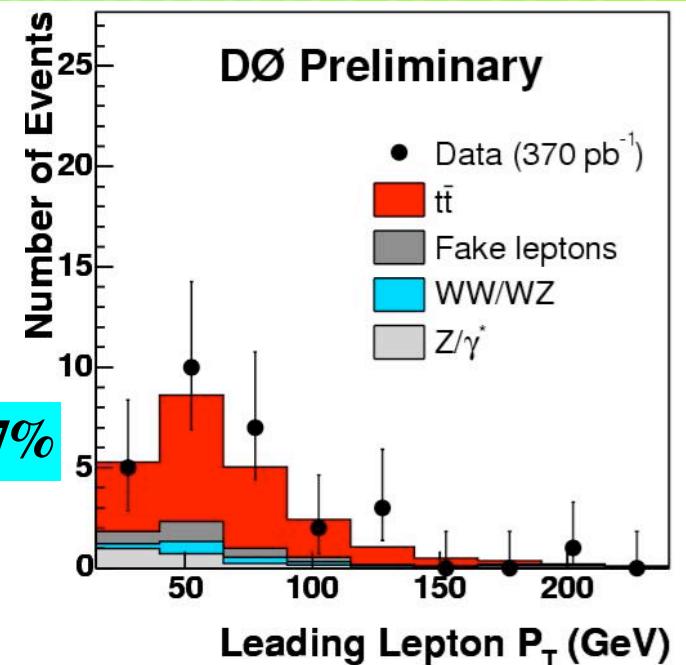
Run 193332 Evt 3472458 Tue Jan 25 15:58:40 2005

ET scale: 54 GeV

$$\varepsilon \times BR(t\bar{t} \rightarrow \text{dilepton}) \approx 0.7\%$$



- 2 isolated electrons/muons  $p_T > 15 \text{ GeV}/c$
- At least 2 jets  $p_T > 20 \text{ GeV}/c$
- Reduce backgrounds:
  - $Z/\gamma^* \rightarrow ee$  with MET and sphericity
  - $Z/\gamma^* \rightarrow \mu\mu$  with MET and  $\chi^2$  consistency with Z mass
  - $Z/\gamma^* \rightarrow \tau\tau \rightarrow e\nu_e \nu_\tau \mu\nu_\mu \nu_\tau$  with  $\Sigma p_T$  of jets and leading lepton
  - Instrumental with multivariate likelihood electron id in ee channel



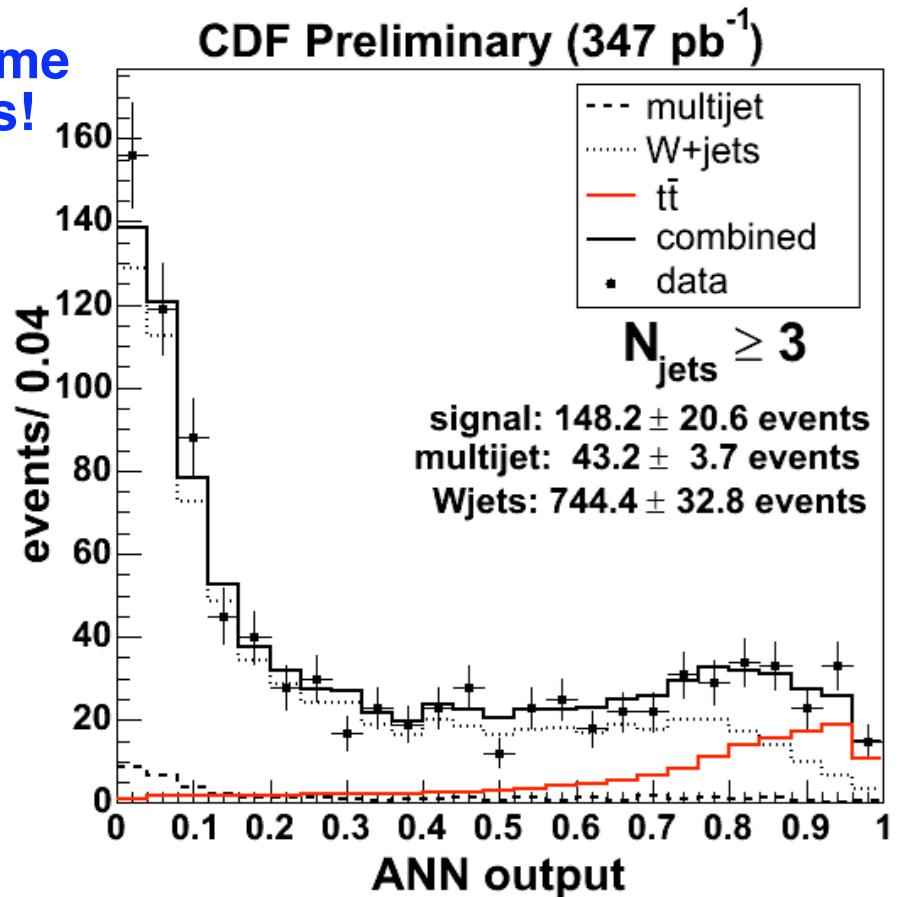
# Lepton+Jets

1 isolated electron/muon  $p_T > 20 \text{ GeV}/c$   
At least 3 jets  $p_T > 15 \text{ GeV}/c$   
MET  $> 20 \text{ GeV}$

$$\varepsilon \times BR(t\bar{t} \rightarrow l + jets) \approx 7\%$$

Need more discrimination against same final state from W+jets processes!

Kinematic event observables  
Decay products of massive top quarks more energetic and central than W+jets  
Combine several kinematic observables in optimal artificial neural network  
Fit observed data to expected distributions from signal and backgrounds



$$\sigma(t\bar{t}) = 6.3 \pm 0.8(\text{stat}) \pm 0.9(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}$$

# Lepton+Jets with b-tagging

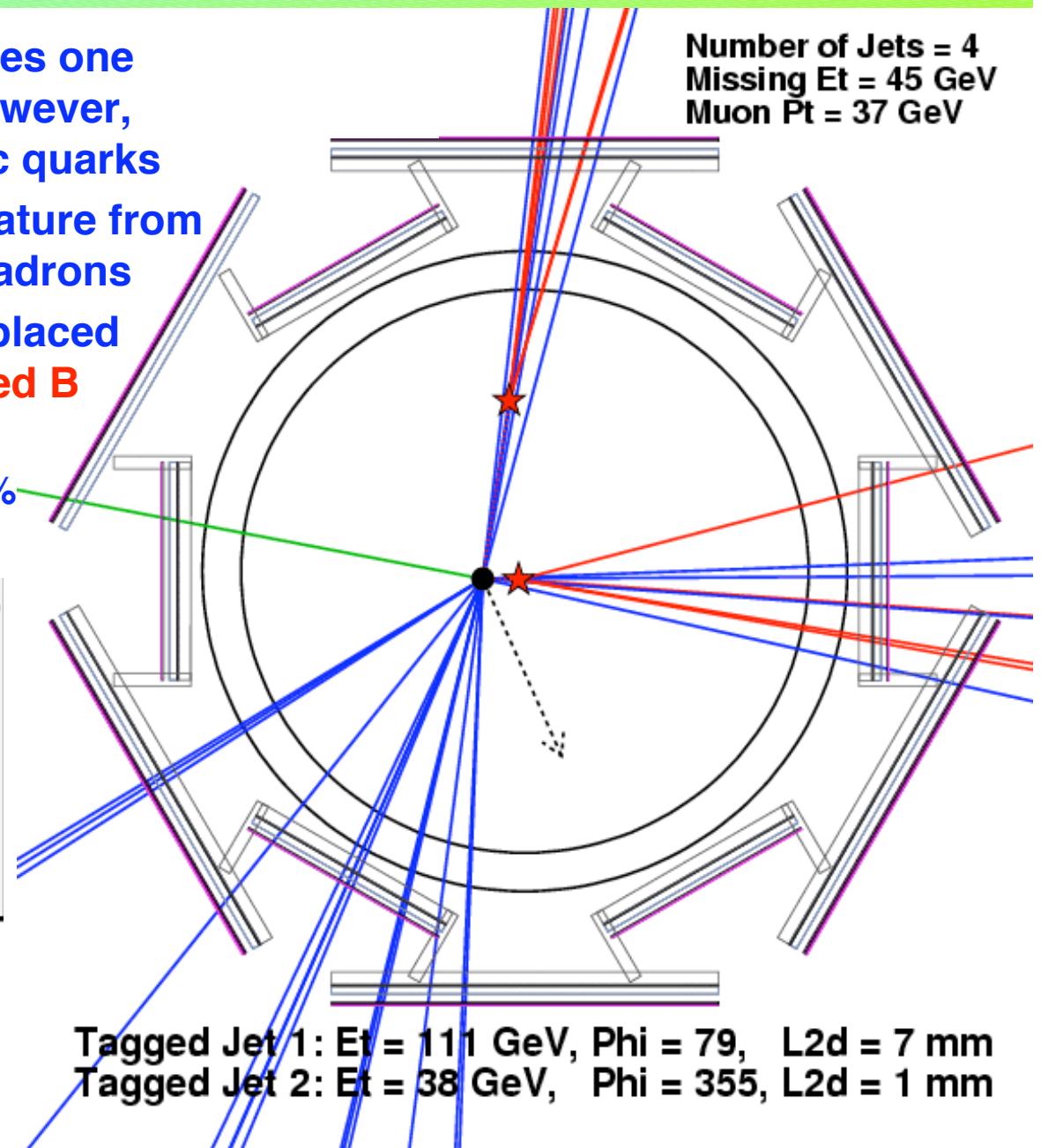
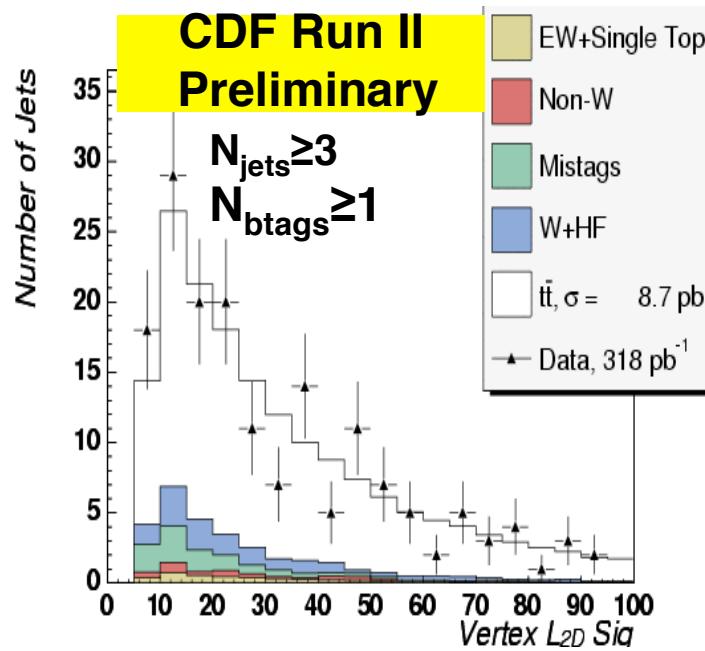
Each top quark decay produces one energetic central b-quark, however, only few % W+jets have b or c quarks

Distinctive experimental signature from long lifetimes of massive B hadrons

Reconstruct significantly displaced secondary vertex from charged B decay products inside jet

Efficiency per b-jet about 50%

False positive rate about 1%



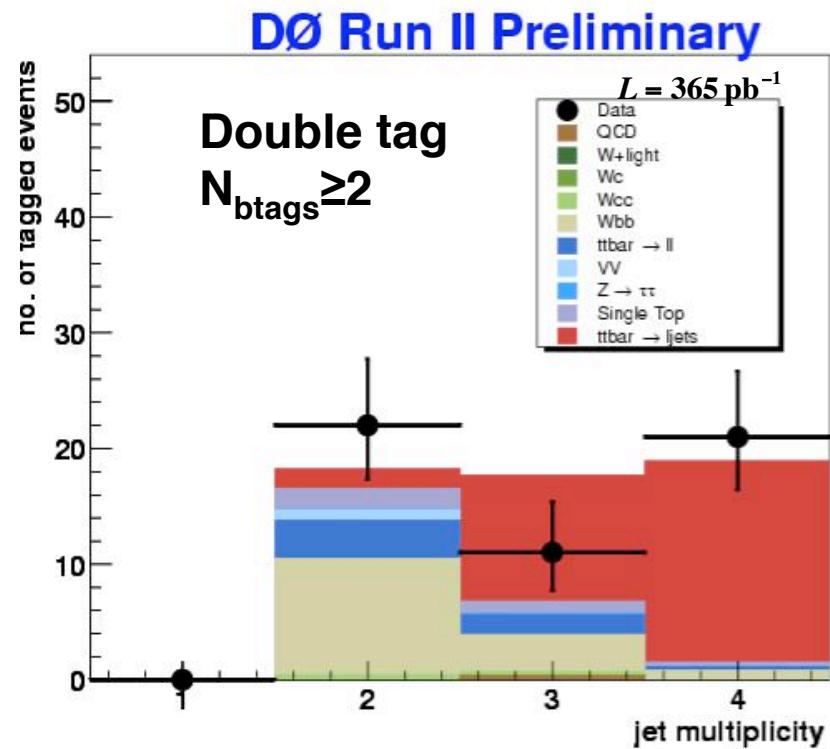
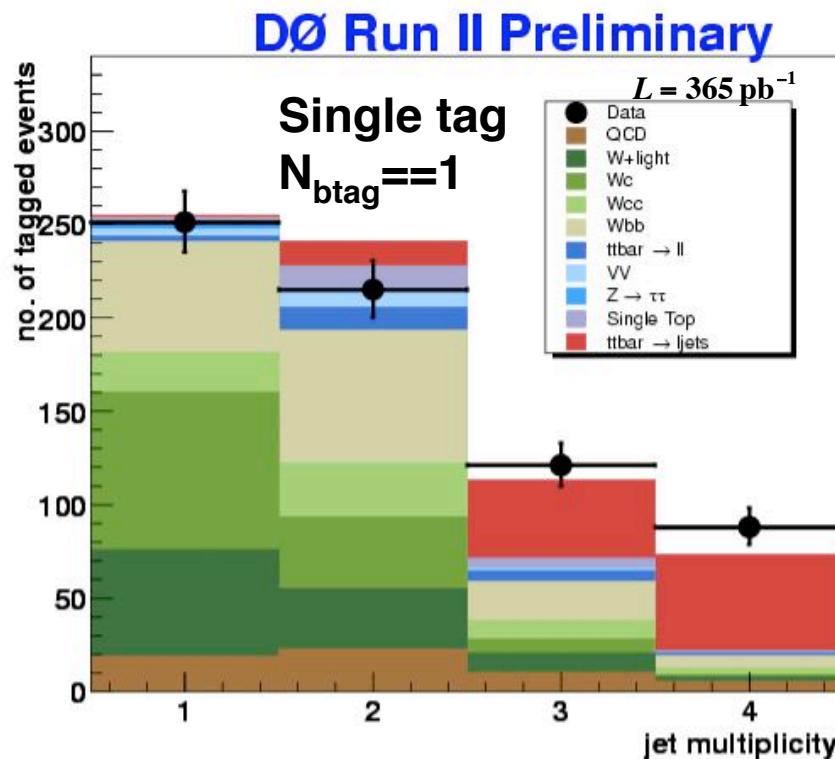
# Lepton+Jets with b-tagging

$$\varepsilon \times BR(t\bar{t} \rightarrow l + jets) \approx 4\%$$

$$\sigma(t\bar{t}) = 8.1 \pm 0.9(\text{stat}) \pm {}^{0.9}_{0.8}(\text{syst}) \pm 0.5(\text{lumi}) \text{ pb}$$

Events	Control region		Signal region	
$N_{\text{btag}}=1$	W+1 jet	W+2 jets	W+3 jets	W+ $\geq 4$ jets
Bkg	$254 \pm 38$	$228 \pm 31$	$71 \pm 9$	$22 \pm 2$
Data	251	215	121	88

Events	Control		Signal region	
$N_{\text{btags}} \geq 2$	W+2 jets	W+3 jets	W+ $\geq 4$ jets	
Bkg	$17 \pm 3$	$7 \pm 1$	$1.9 \pm 0.3$	
Data	22	11	21	



# $e\tau_h$ and $\mu\tau_h$

$$\varepsilon \times BR(t\bar{t} \rightarrow e\tau_h, \mu\tau_h) \approx 0.08\%$$

1 isolated electron/muon  $p_T > 20$  GeV/c

- 1 isolated  $\tau \rightarrow \nu_\tau + \text{hadrons}$   $p_T > 15$  GeV/c
- MET > 20 GeV
- At least 2 jets  $p_T > 20$  GeV/c

Reduce backgrounds

- Total transverse energy > 205 GeV
- Not compatible with  $Z \rightarrow \tau\tau$

Events (195 pb $^{-1}$ )	$e\tau_h$	$\mu\tau_h$
Bkg	$0.8 \pm 0.1$	$0.5 \pm 0.1$
Data	2	0

CDF set limit on anomalous decay rate

$$\frac{\Gamma(t \rightarrow \tau\nu_\tau q)}{\Gamma_{SM}(t \rightarrow \tau\nu_\tau q)} < 5.2 \text{ @ 95% C.L.}$$

# Neutrino+jets

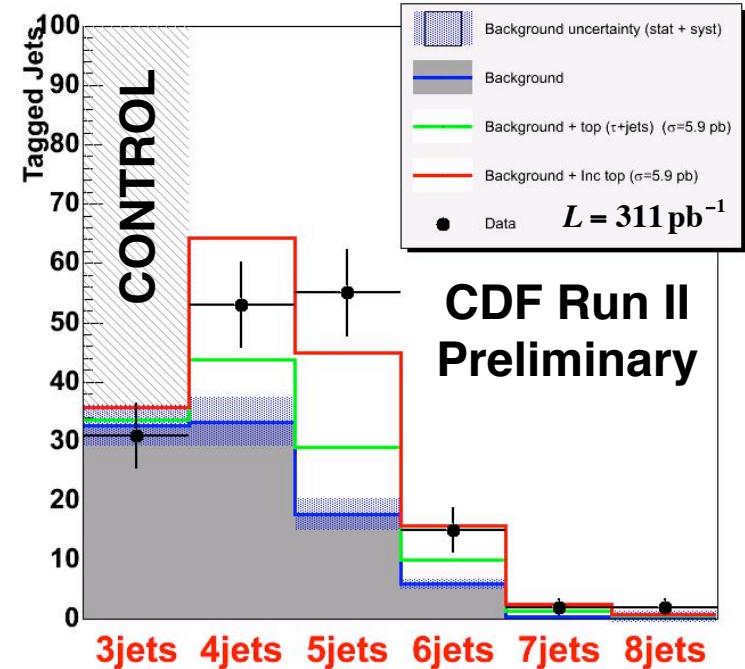
$$\varepsilon \times BR(t\bar{t} \rightarrow \nu + \text{jets}) \approx 4\%$$

Zero isolated electrons/muons!

- At least 4 jets  $p_T > 15$  GeV/c
- MET significance > 4 GeV $^{1/2}$
- MET not collinear with jets
- At least 1 b-tag

In future: explicit tau identification!

$$\sigma(t\bar{t}) = 6.1 \pm 1.2(\text{stat}) \pm 1.3(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}$$



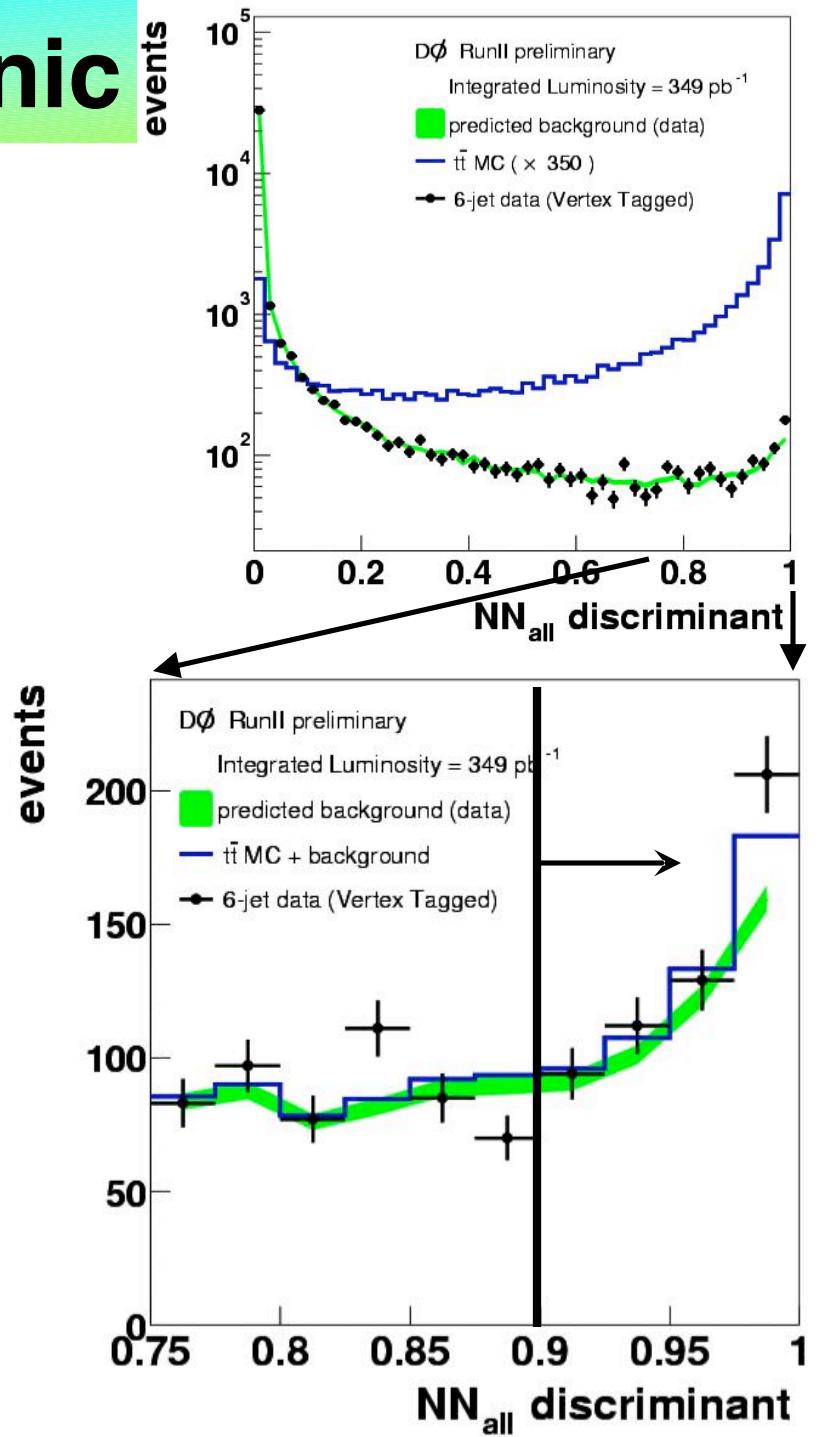
# All-hadronic

- At least 6 jets with  $p_T > 15 \text{ GeV}/c$
- Reduce huge background from QCD processes at a hadron collider!
- At least one b-tag
  - Combine kinematic observables in artificial neural network
  - Require  $NN > 0.9$

$$\varepsilon \times BR(t\bar{t} \rightarrow \text{all - hadronic}) \approx 3\%$$

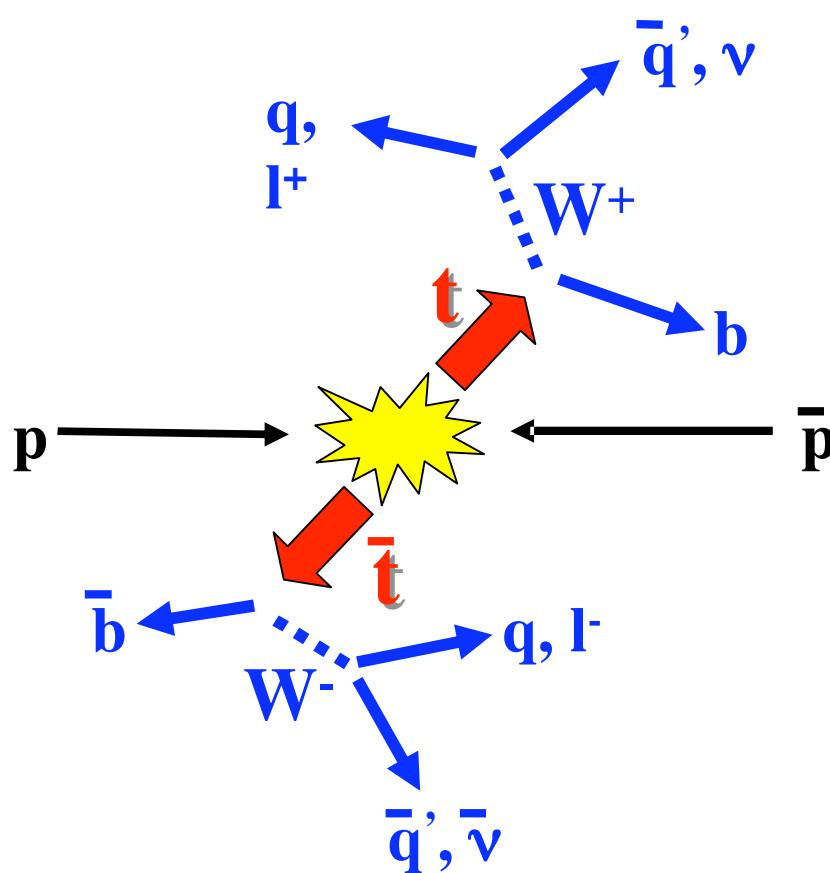
Events	All-hadronic
Raw Bkg	$494 \pm 5$
Corrected Bkg	$482 \pm 5$
Data	541

$$\sigma(t\bar{t}) = 5.2 \pm^{2.6}_{2.5} (\text{stat}) \pm^{1.5}_{1.0} (\text{syst}) \pm 0.3 (\text{lumi}) \text{ pb}$$



# Is this the standard model Top Quark?

Observe Top Quark Pair Production  
in all final states



Search for Single Top Quark Production

Test Top Quark Decay

Top always decays to  $W^+b$ ?

Any Charged Higgs from  $t \rightarrow H^+b$ ?

Top electric charge is +2/3?

W helicity “right”?

Anomalous FCNC  $t \rightarrow Zc, gc, \gamma cb$ ?

Test Top Quark Pair Production

Pair Production Rate

New massive resonance  $X \rightarrow t\bar{t}$ ?

Top spin

Tests of NLO kinematics

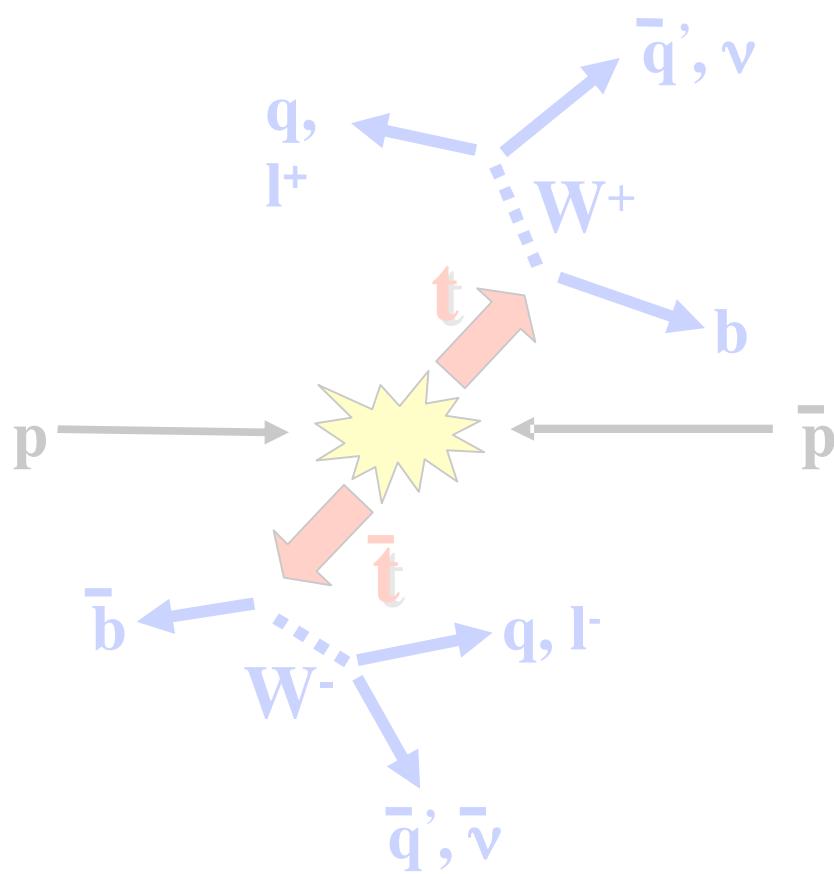
Precision measurement

of top quark mass:

30% improvement this year!

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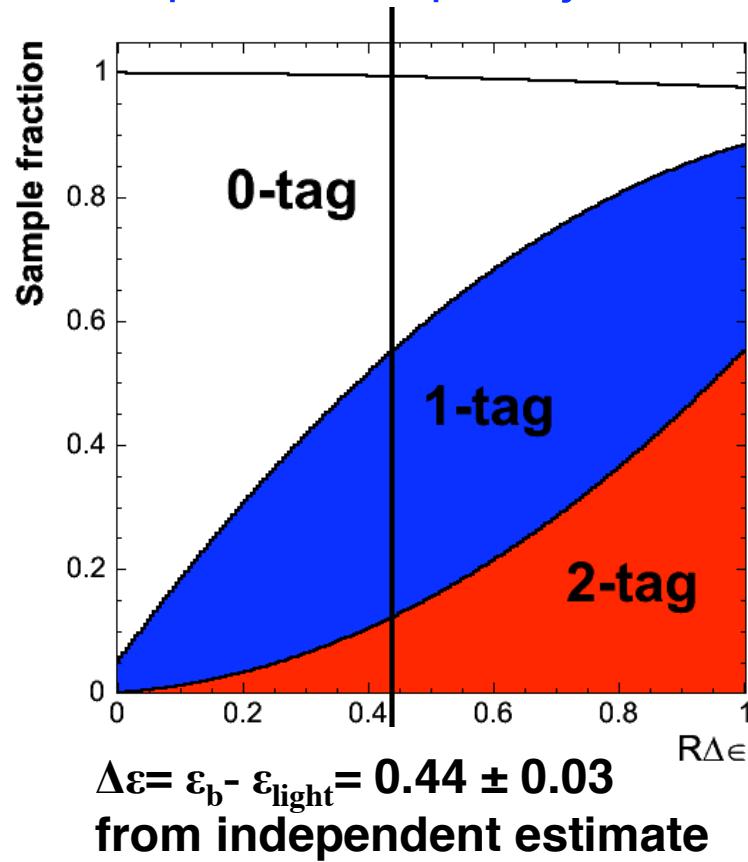
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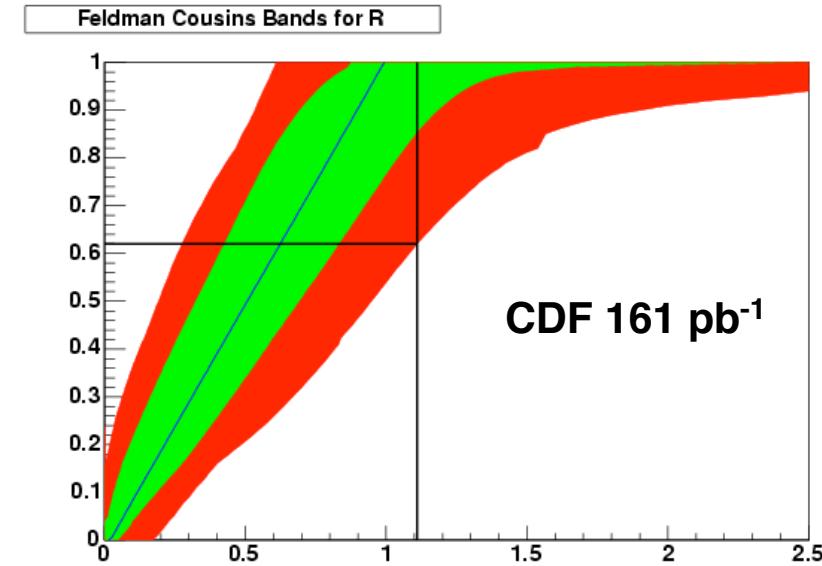
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# Does top always decay to W<sup>+</sup>b? Part (b)

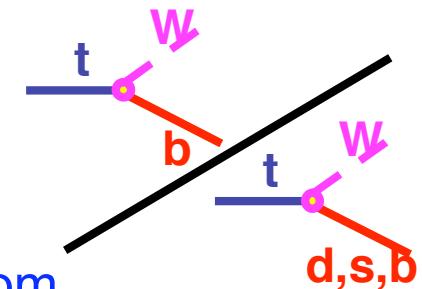
- If  $\text{BR}(t \rightarrow Wb)$  is lower than SM prediction of  $\sim 100\%$ , or if b-tag efficiency is lower than estimated value
  - observe fewer double b-tag events
  - observe more events without any b-tags
- Fit  $R = \text{BR}(t \rightarrow Wb) / \text{BR}(t \rightarrow Wq)$  times b-tag efficiency from observed number and estimated composition of 0,1,2-tag dilepton and lepton+jets events



$$\text{Best fit } R = 1.11 \pm^{0.21}_{0.26}$$



$R > 0.62 @ 95\% \text{ C.L.}$



# Does top always decay to $W^+b$ ? Part (W)

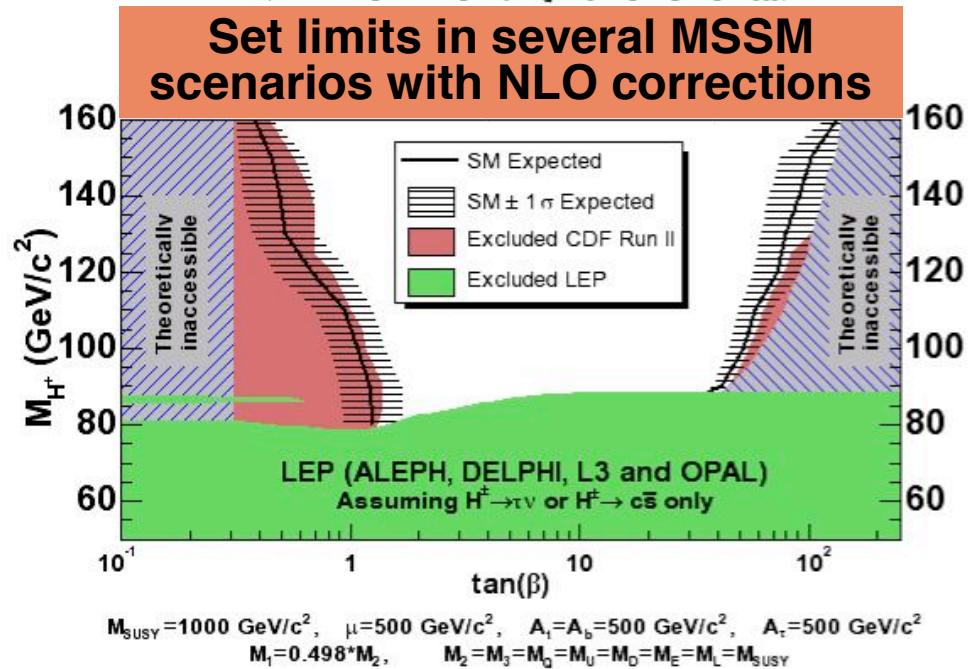
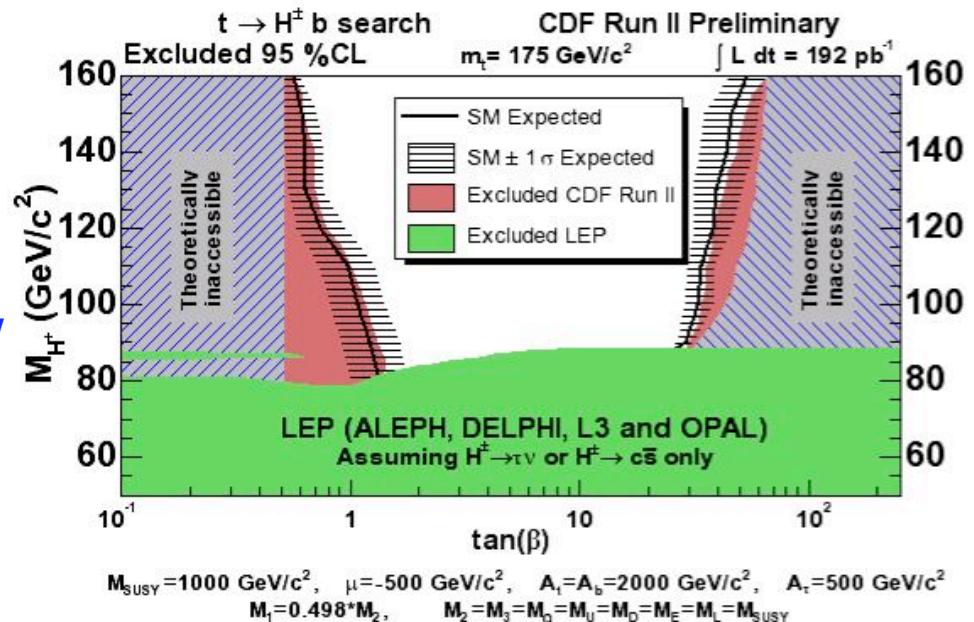
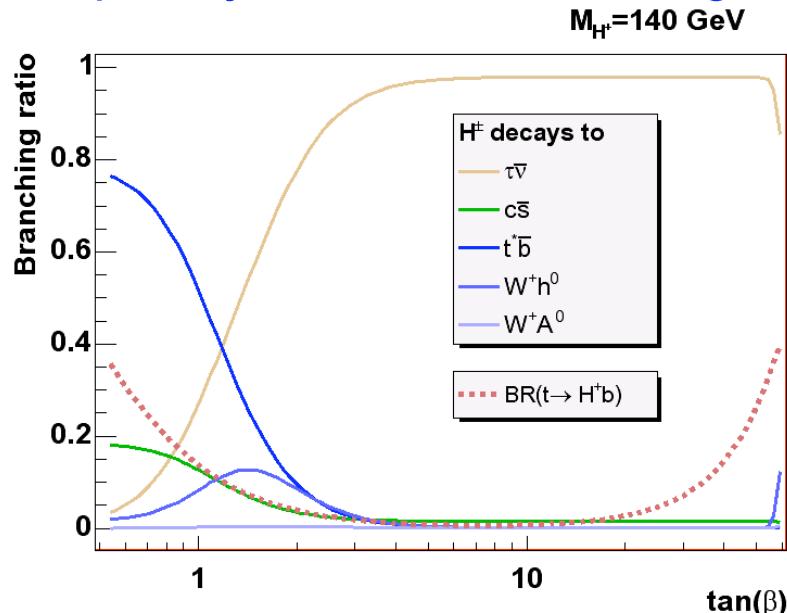
Branching ratio for  $t \rightarrow H^+b$  significant ( $>10\%$ ) for small and large  $\tan\beta$

$H^+$  decays differently than  $W^+$

$H^+ \rightarrow \tau^+ \nu_\tau$  enhanced if high  $\tan\beta$ : observe more taus!

$H^+ \rightarrow t^* b \rightarrow W^+ b b$  for high  $m(H^+)$  if low  $\tan\beta$ : mimics SM signature but observe more b-tags

Compare number of observed events in 4 final states: dilepton,  $e\tau_h + \mu\tau_h$ , lepton+jets with single b-tag, and lepton+jets with double b-tags



# Does top always decay to $W^+b$ ? Part ( $W^+$ )

Electric charge of  $+2/3$  implies  $t \rightarrow W^+b$

Electric charge of  $-4/3$  implies  $t \rightarrow W^-b$

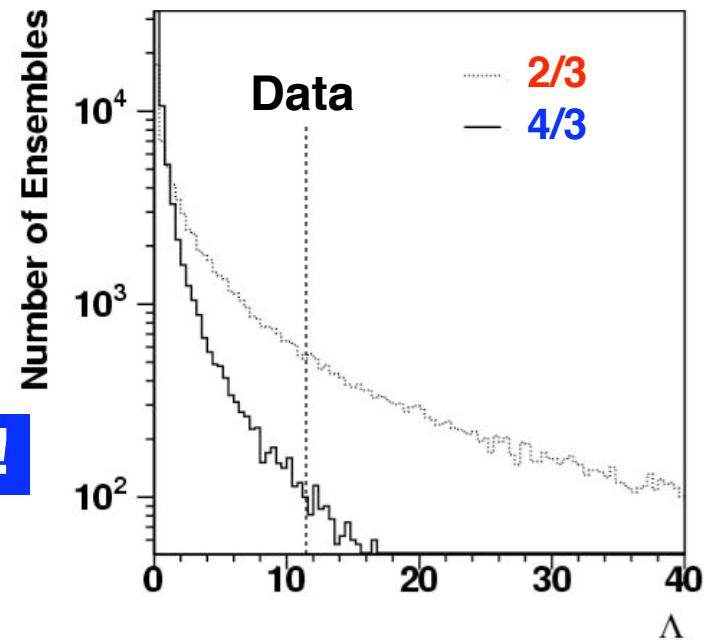
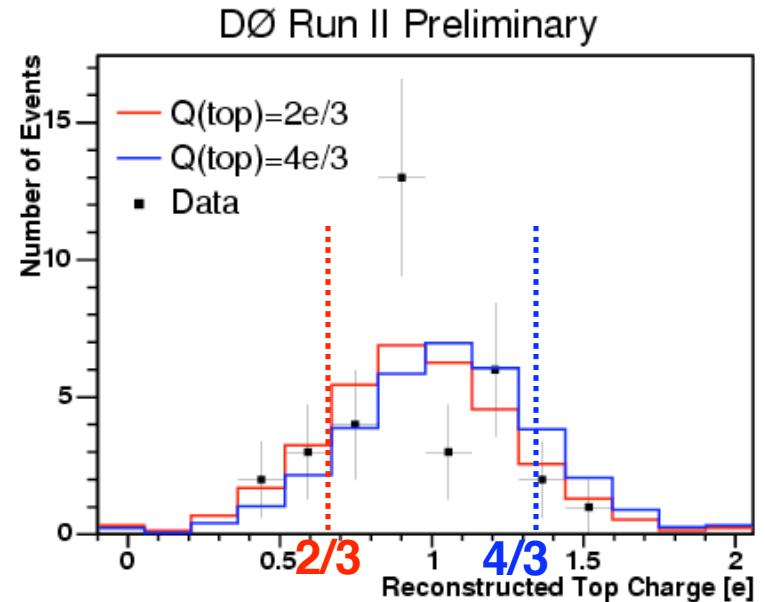
How to tell the difference experimentally?

- Select 21 double b-tag lepton+ $\geq 4$  jets
  - Very pure sample with only 5% bkg
  - Statistical estimate b charge from jet-charge
- Pick best lepton and b-jet combination with kinematic fit for fixed  $m_{top} = 175 \text{ GeV}/c^2$  hypothesis
  - 17 double b-tag events pass
  - Correct assignment  $79 \pm 2\%$
- Calculate magnitude of “top” charges
  - $Q_1 = l$  lepton charge +  $b_1$ -jet chargel
  - $Q_2 = l$ -lepton charge +  $b_2$ -jet chargel
- Define  $\Lambda$  as ratio of unbinned likelihoods for SM ( $Q=+2/3$ ) and Exotic ( $Q=-4/3$ ) hypotheses

Measure  $\Lambda = 11.5$

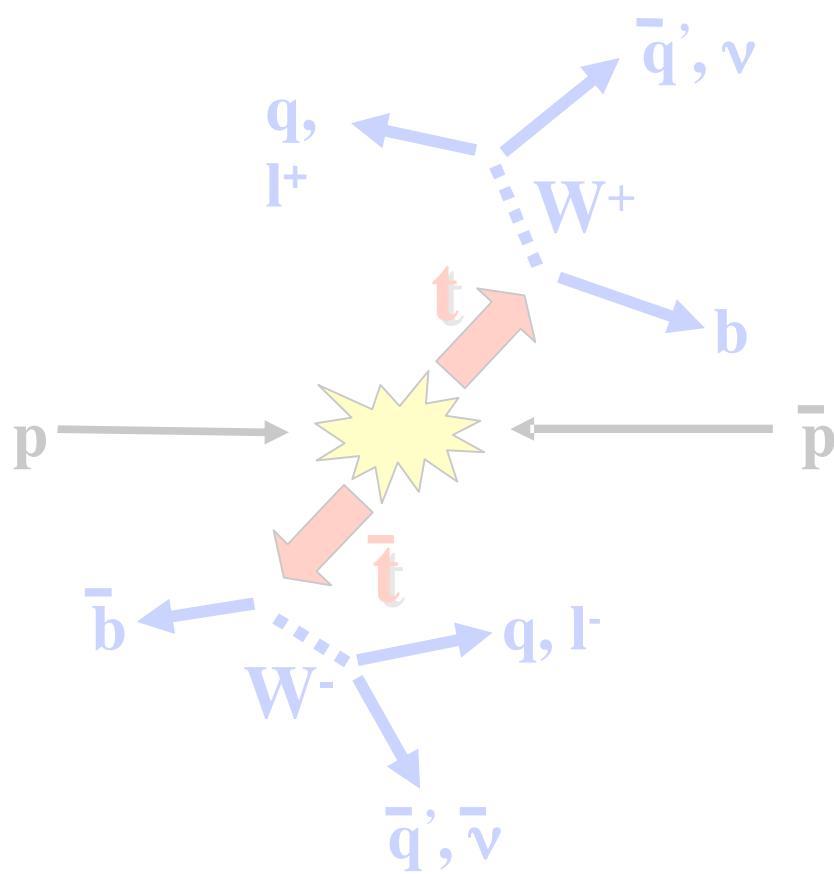
Exclude  $Q = -4/3$  @ 94% C.L.

First result!



# Decay consistent with standard model so far!

Observe Top Quark Pair Production  
in all final states



Search for Single Top Quark Production

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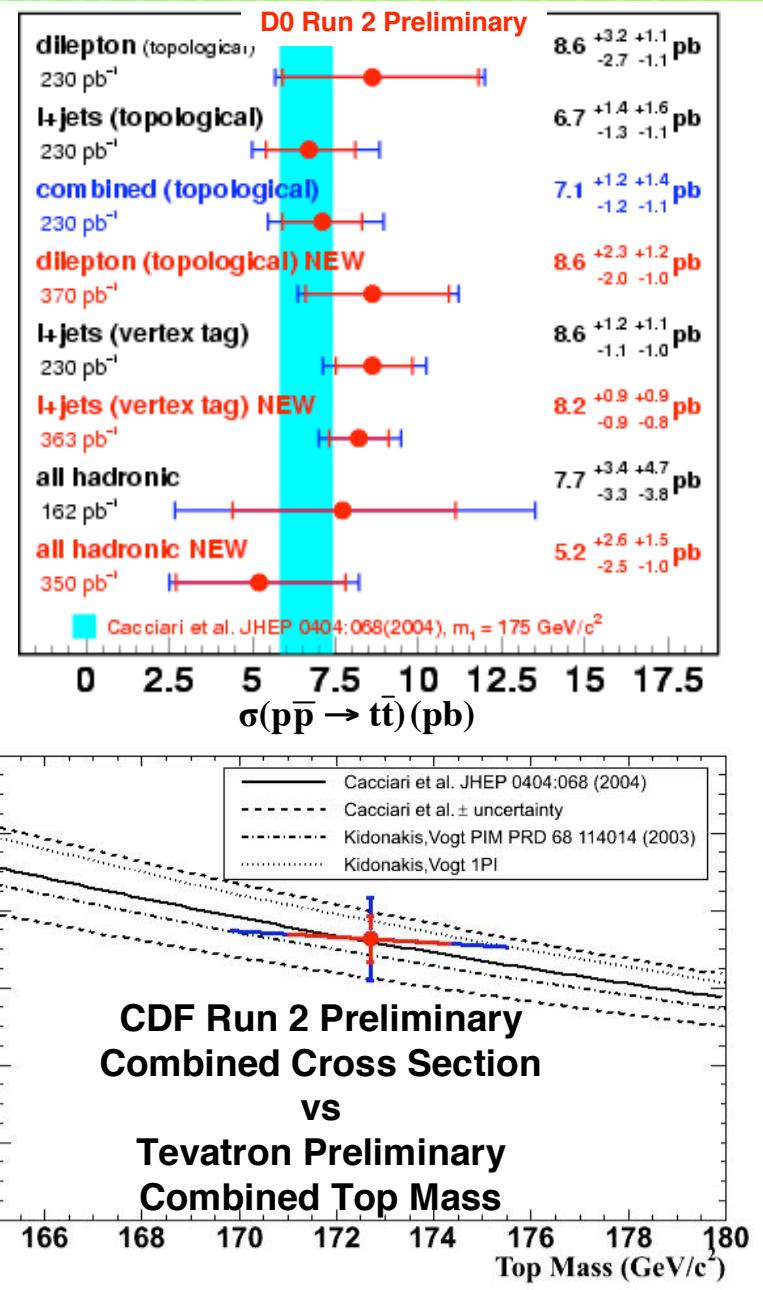
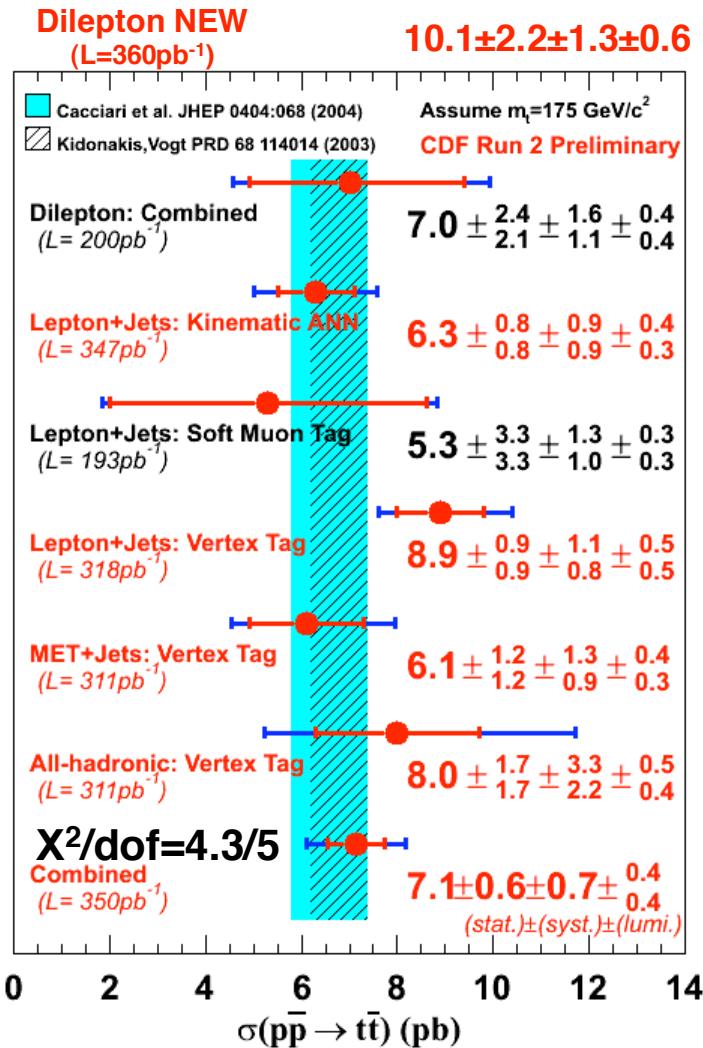
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# Top Pair Production Rate

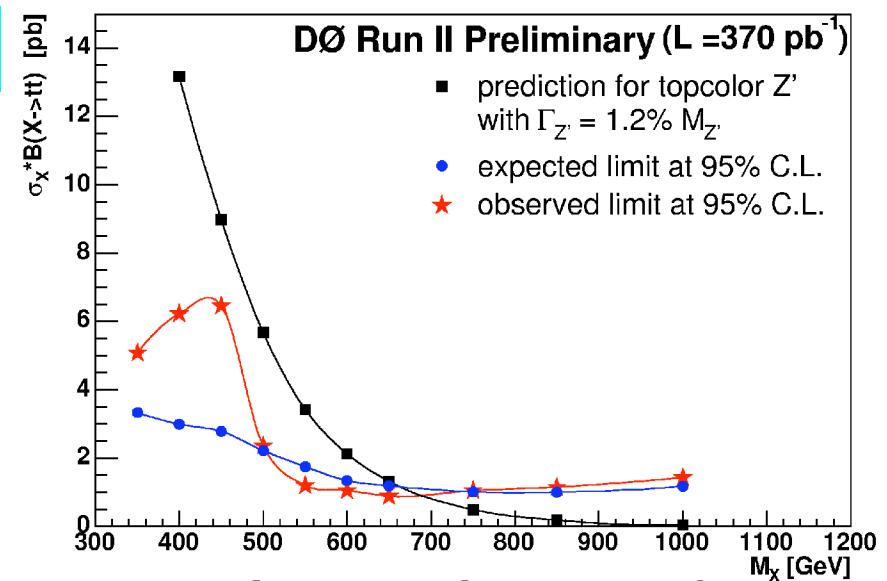
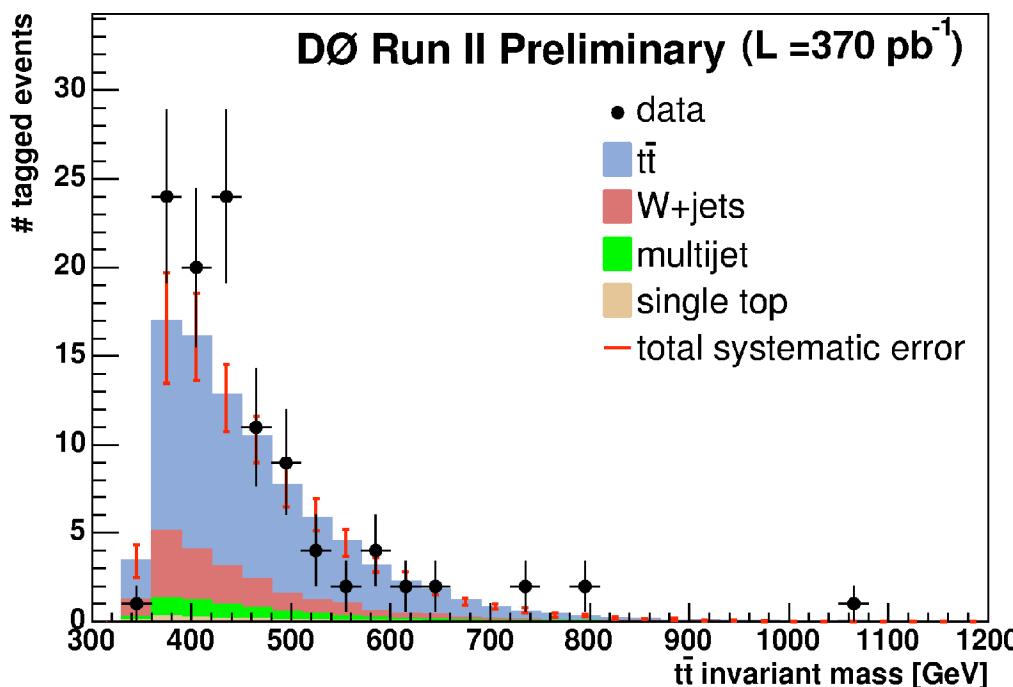
- Are measurements in different final states consistent with each other and with theory?



# Does something new produce ttbar?

- Search for new massive resonance decaying to top pairs
  - Lepton+ $\geq 4$  jets with  $\geq 1$  b-tags
  - Kinematic fit to ttbar hypothesis to improve experimental resolution on invariant mass of ttbar system
- Fix SM backgrounds to expected rate
  - Use theory prediction of 6.7 pb for SM top pair production

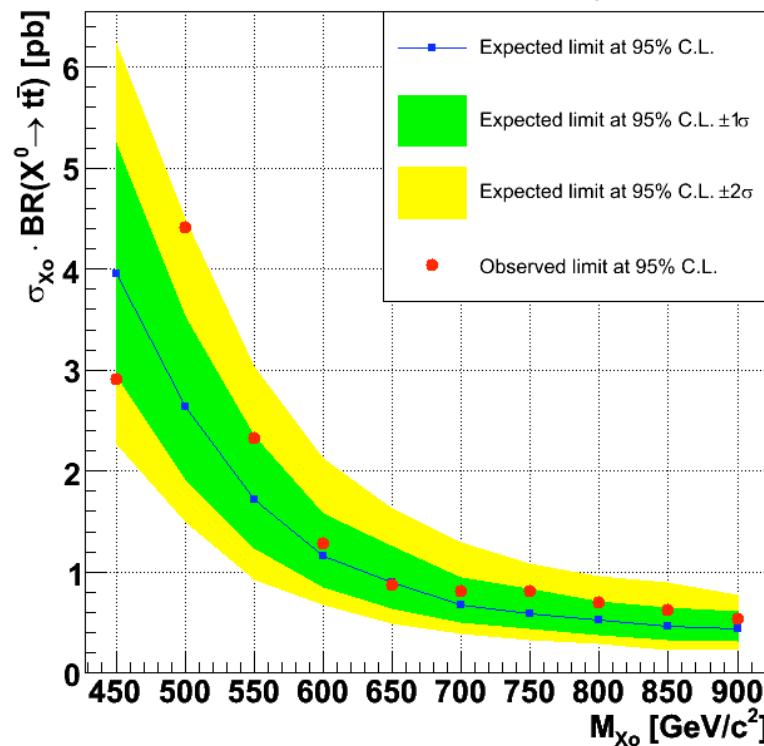
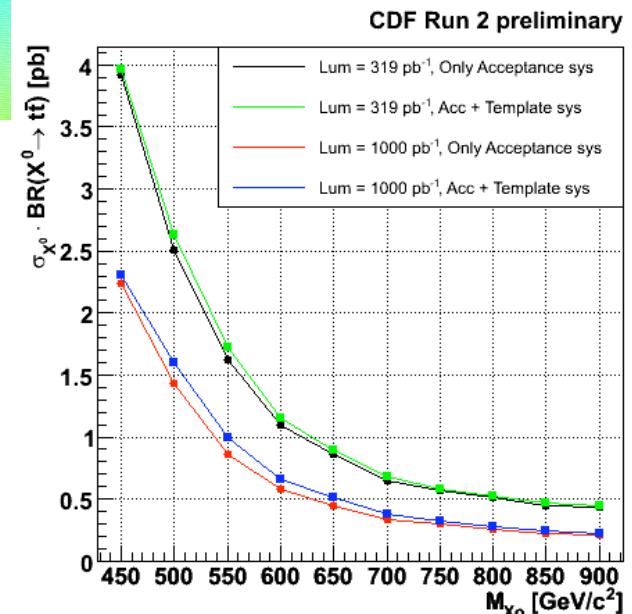
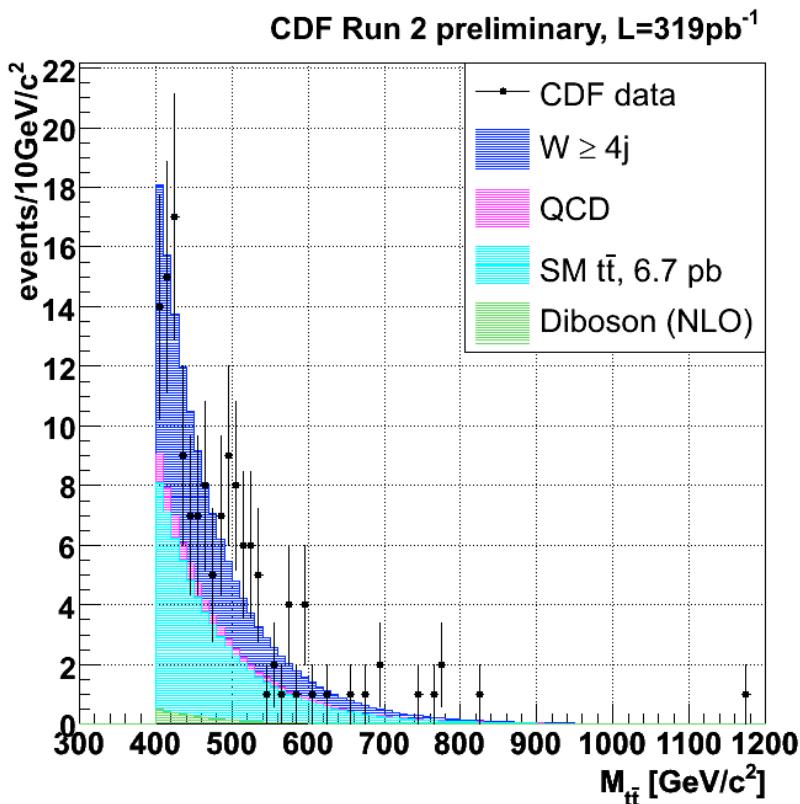
Derive limit on  $\sigma_X \times BR(X \rightarrow t\bar{t})$



Interpret in terms of  
one  
of many possible models:  
topcolor assisted technicolor  $Z'$

# What does CDF observe?

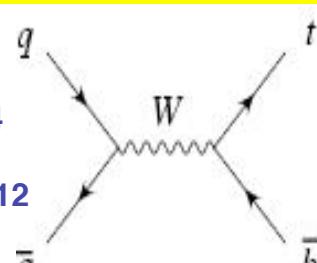
- Lepton+ $\geq 4$  jets (no b-tagging)
  - Matrix element technique to increase sensitivity
- Fix top pair, diboson, QCD to expected rates
  - Assume everything else is W+jets
- Also see excess around 500 GeV/c<sup>2</sup>
  - Only 2 std. dev. now...could be interesting result with 3xdata for Moriond 2006



# Does something new produce Single Top Quarks?

Single top quark production via electroweak interaction  
Cross section proportional to  $|V_{tb}|^2$

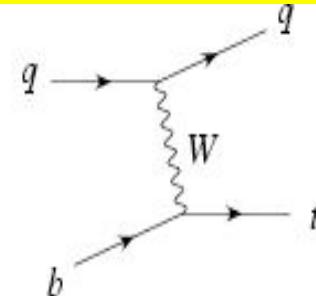
Harris et al PRD 66 (02) 054024  
Cao et al hep-ph/0409040  
Campbell et al PRD 70 (04) 094012



$0.88 \pm 0.11 \text{ pb}$

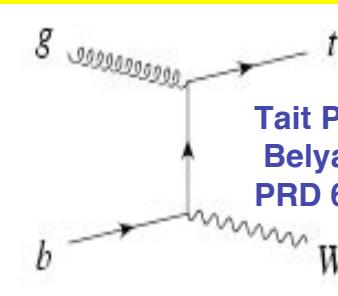
Trigger on lepton from  $t \rightarrow W b \rightarrow \ell \nu b$

2 b-jets for s-channel



$1.98 \pm 0.25 \text{ pb}$

1 b-jet and 1 light jet for t-channel



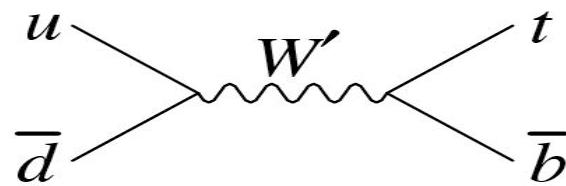
Tait PRD 61 (00) 034001  
Belyaev, Boos  
PRD 63 (01) 034012

<0.1 pb

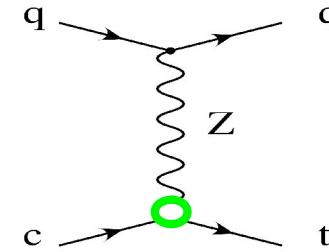
Interesting to measure both channels – sensitive to different physics

See Tait, Yuan  
PRD63, 014018 (2001)

s-channel  
Sensitive to new resonances



t-channel  
Sensitive to FCNCs

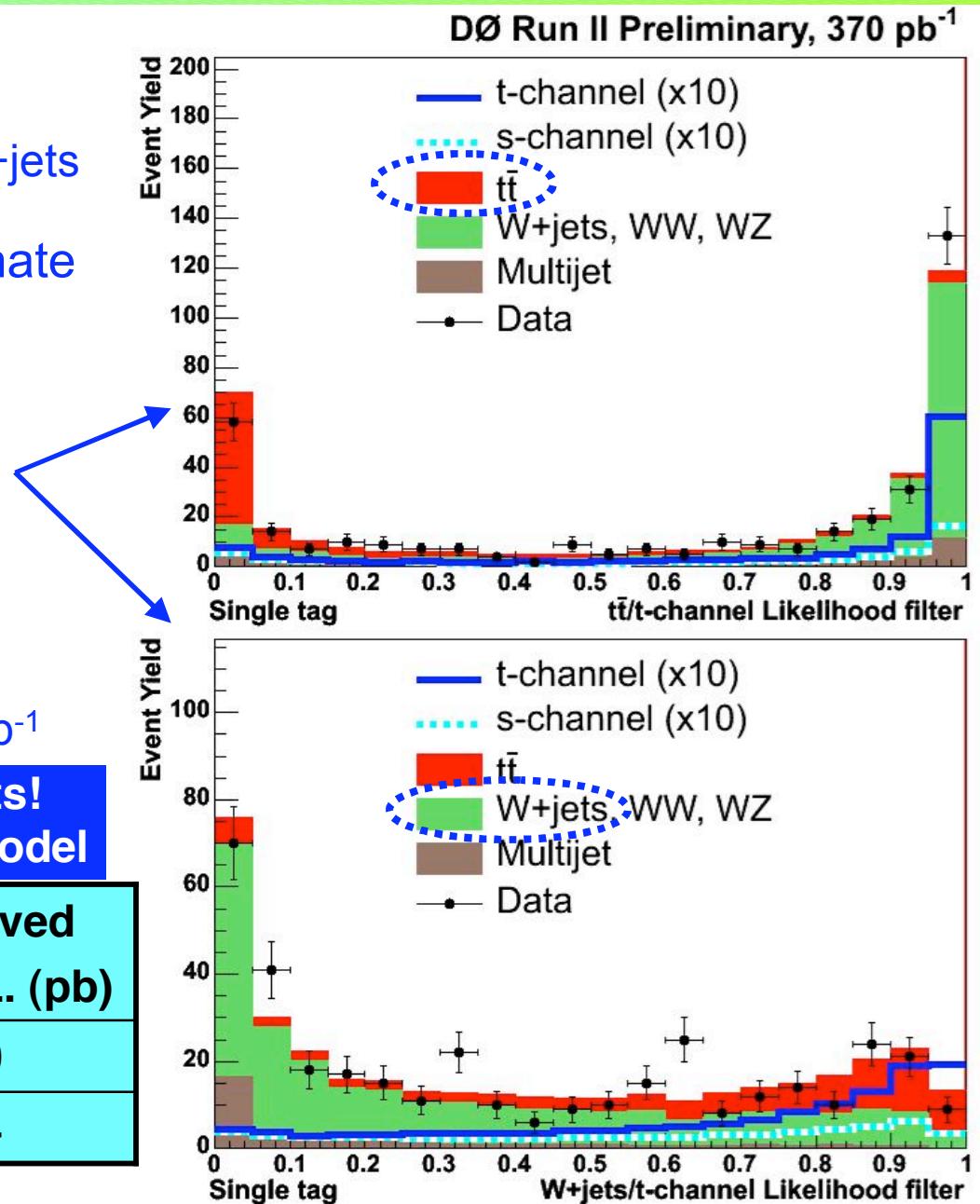


# Search for Single Top Quark Production

- Why is it difficult?
  - Signal swamped by W+jets
  - Signal sandwiched between W+jets and top pair production
- Dedicated likelihood to discriminate between each signal and each background
  - Kinematic observables
  - Show likelihoods for t-channel
- Rely on good MC modeling of W+jets background composition and kinematics
  - Big challenge for discovery!
  - $3\sigma$  evidence expected with  $<2 \text{ fb}^{-1}$

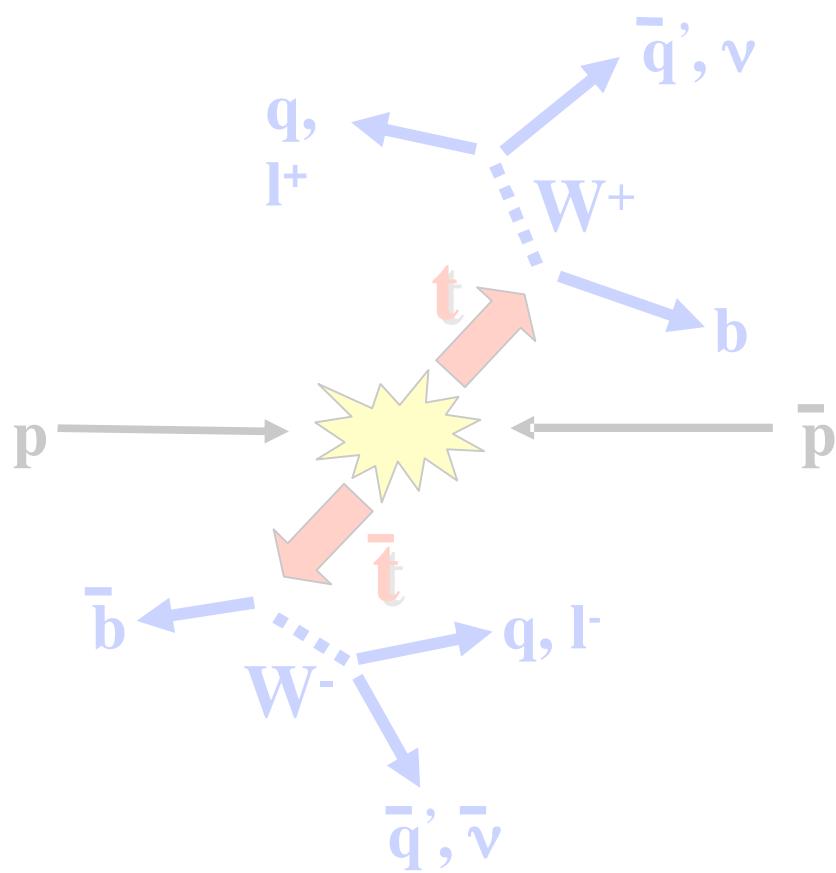
**D0 Preliminary: World's best limits!  
Factor of 2-3 away from standard model**

D0 $370 \text{ pb}^{-1}$	Expected 95% C.L. (pb)	Observed 95% C.L. (pb)
s-channel	3.3	5.0
t-channel	4.3	4.4



# Production & Decay consistent with standard model

Observe Top Quark Pair Production  
in all final states



Search for Single Top Quark Production

Test Top Quark Decay

Top always decays to  $W^+b$ ?

Any Charged Higgs from  $t \rightarrow H^+b$ ?

Top electric charge is +2/3?

W helicity “right”?

Anomalous FCNC  $t \rightarrow Zc, gc, \gamma cb$ ?

Test Top Quark Pair Production

Pair Production Rate

New massive resonance  $X \rightarrow tt$ ?

Top spin

Tests of NLO kinematics

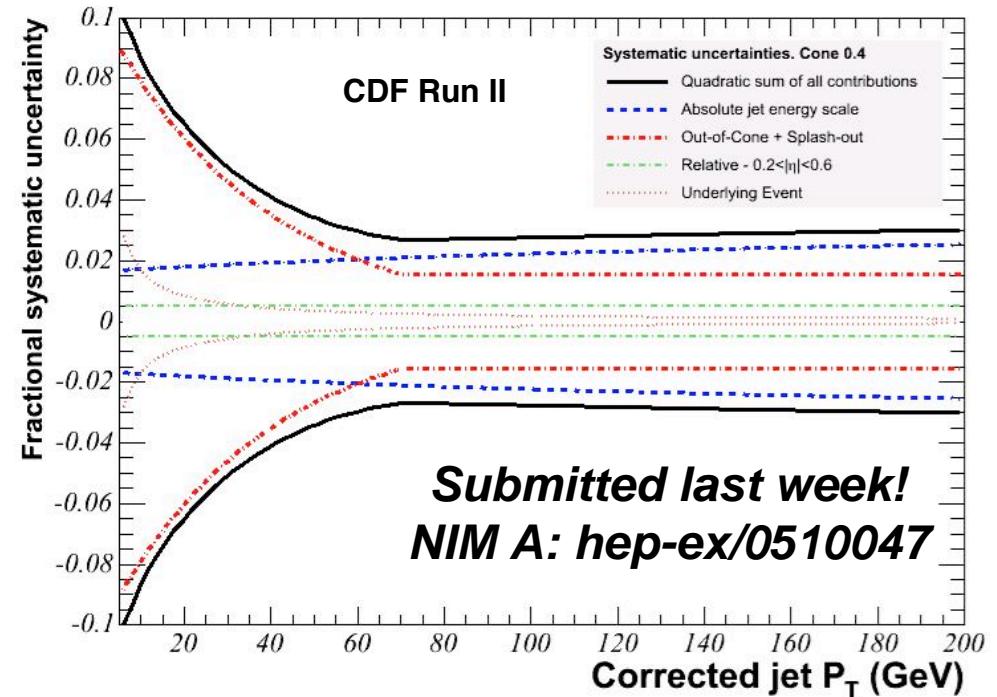
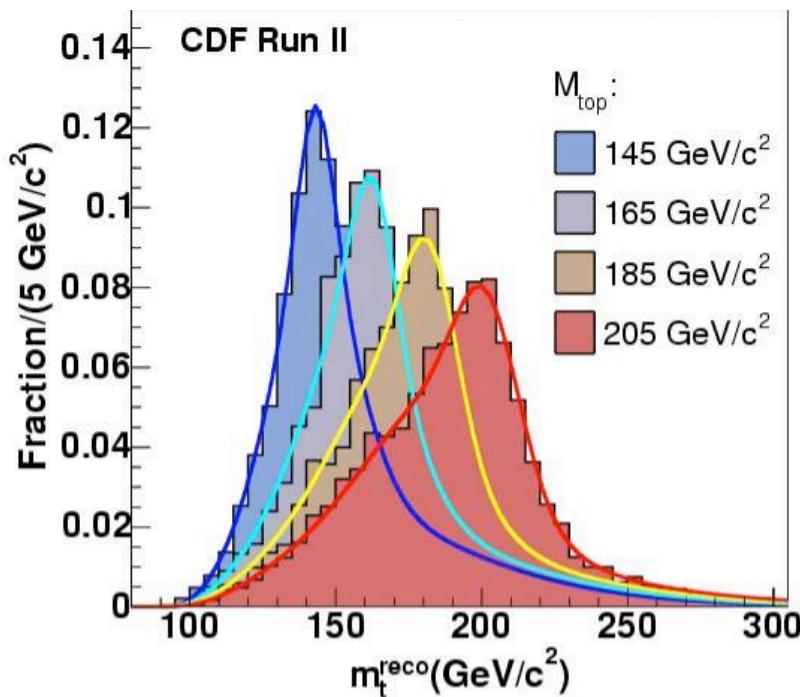
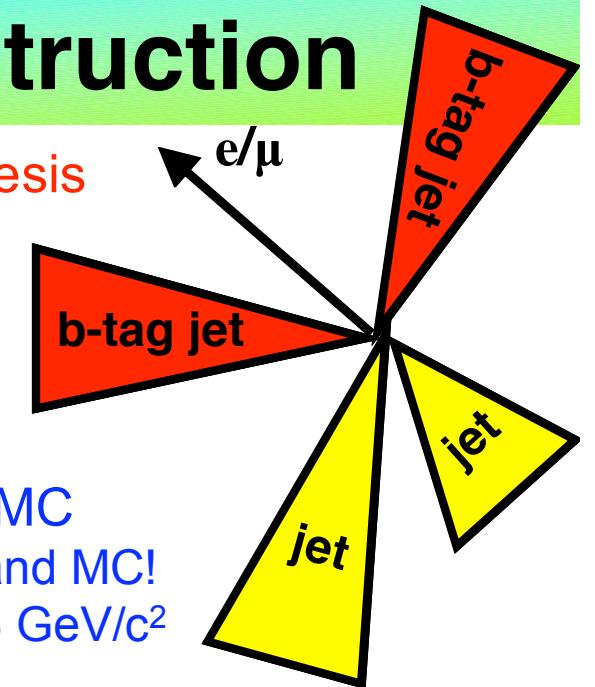
Precision measurement

of top quark mass:

30% improvement this year!

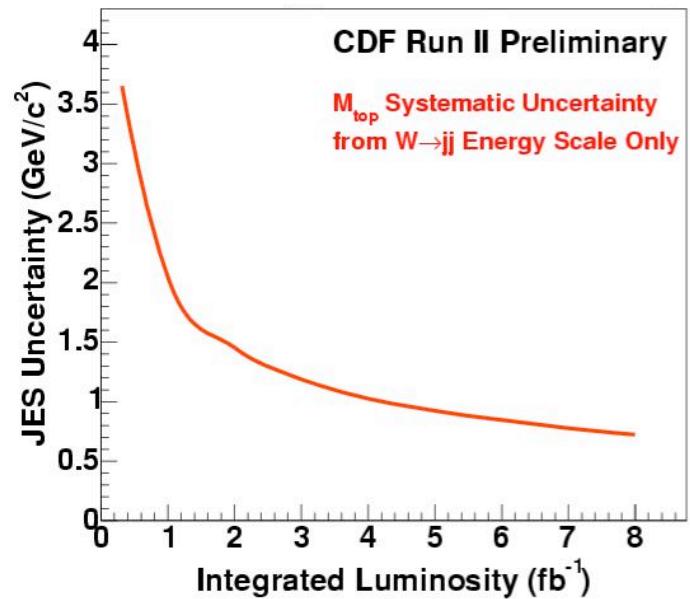
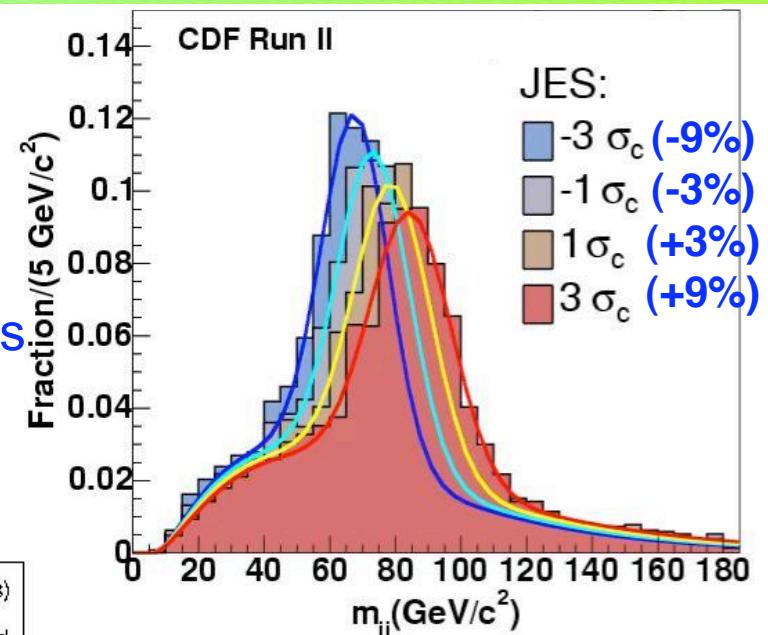
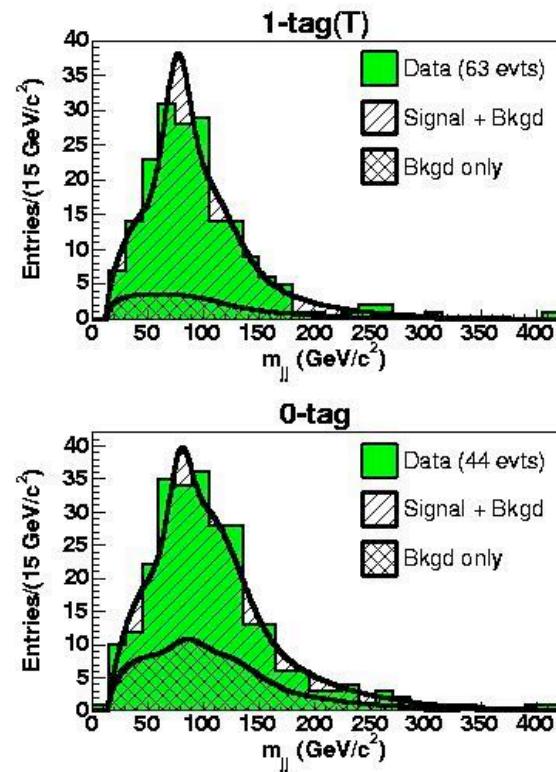
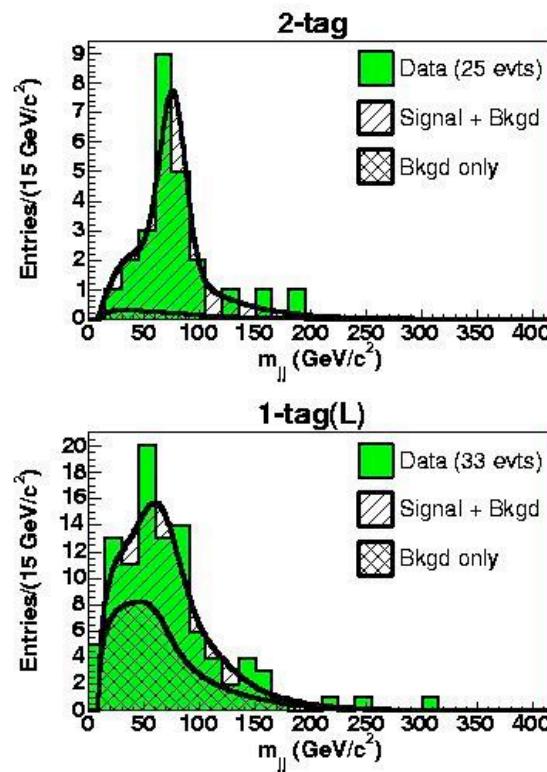
# Top Quark Mass: Reconstruction

- Kinematic fit to top pair production and decay hypothesis
  - Obtain improved resolution on reconstructed top mass
  - Choose most consistent solution for  $t \rightarrow jjb$  and  $t \rightarrow l b\bar{b}$ 
    - 24 possibilities for 0 b-tags
    - 12 possibilities for 1 b-tag
    - 4 possibilities for 2 b-tags
- Fit data to reconstructed top mass distributions from MC
  - Need excellent calibration of jet energy between data and MC!
  - 3% systematic uncertainty on jet energy scale gives  $\sim 3 \text{ GeV}/c^2$  systematic uncertainty on top quark mass



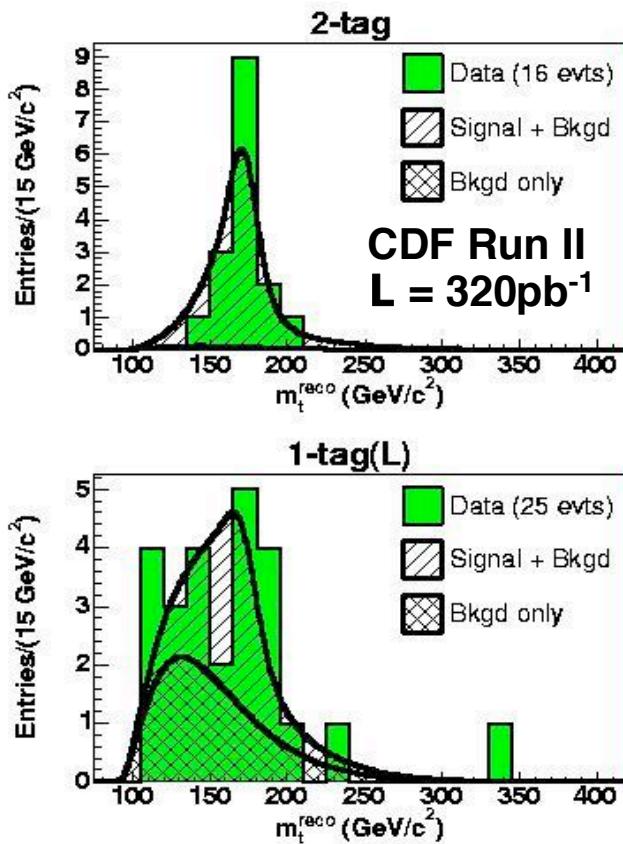
# Top Quark Mass: *in situ* jet energy calibration

- New for 2005! Simultaneous fit of invariant mass of jets from  $W \rightarrow jj$  *in lepton+jets data*
  - Determine global jet energy correction factor
  - Use to correct energy of all jets
- Uncertainty dominated by data  $W \rightarrow jj$  statistics
  - Will decrease  $<1 \text{ GeV}/c^2$  with more data!



# CDF Top Mass Measurement: Lepton+Jets

- Simultaneous fit of reconstructed top mass and  $W \rightarrow jj$  mass
  - Include Gaussian constraint on jet energy scale from *a priori* determination
- Best single measurement! Better than previous Run I CDF+D0 average!



$$m_{top} = 173.5 \pm^{2.7}_{2.6} (\text{stat}) \pm 2.5 (\text{JES}) \pm 1.3 (\text{syst}) \text{ GeV / } c^2$$

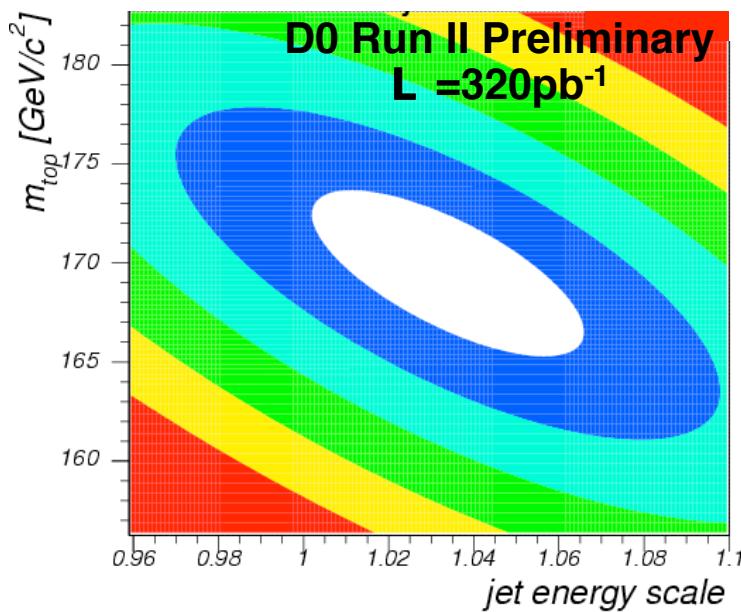
$$\text{JES} = -0.10 \pm^{0.78}_{0.80} \sigma (\text{a priori}) \quad \begin{array}{l} \text{Correction approx. -0.3\%} \\ \text{Uncertainty 20\% smaller} \end{array}$$

**Submitted last week!**  
**PRD: hep-ex/0510048**  
**PRL: hep-ex/0510049**

Systematic Source	Uncertainty ( $\text{GeV}/c^2$ )
ISR/FSR	0.7
Model	0.7
b-jet	0.6
Method	0.6
PDF	0.3
Total	1.3
Jet Energy	2.5

# D0 Top Mass Measurement: Lepton+Jets

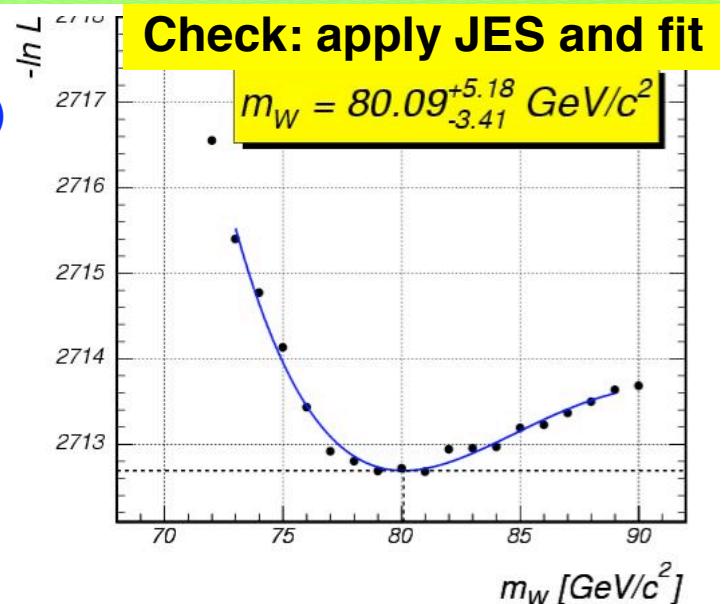
- LO Matrix element technique of Run I
  - Exactly 4 observed jets (150 events,  $32 \pm 5\%$  top)
  - Use LO Matrix element for ttbar and W+jets
  - Weight all 24 possible solutions (no b-tagging)
- New for 2005:  $W \rightarrow jj$  jet energy calibration
  - Fit jet energy scale as well as top mass
  - No *a priori* jet energy determination



$$m_{top} = 169.5 \pm 3.0_{(\text{stat})} \pm 3.2_{(\text{JES})} \pm 1.7_{(\text{syst})} \text{ GeV} / c^2$$

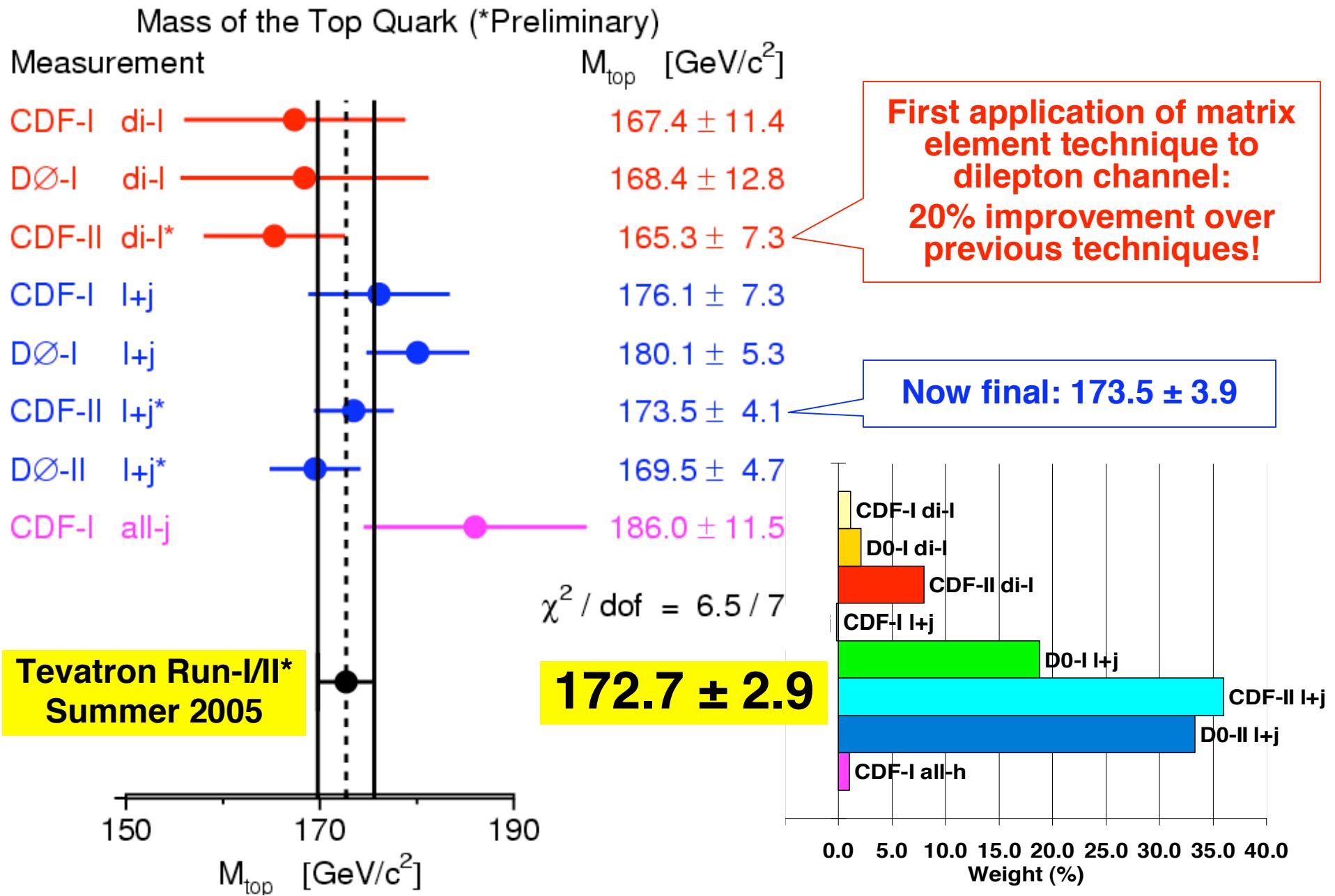
$$\text{JES} = 1.034 \pm 0.034$$

Correction +3.4%  
Uncertainty ±3.4%



Systematic Source	Uncertainty (GeV/c <sup>2</sup> )
ISR/FSR	0.3
Model	0.7
b-jet	1.1
Method	0.9
PDF	0.1
Total	1.7
Jet Energy	3.2

# Tevatron Top Quark Mass

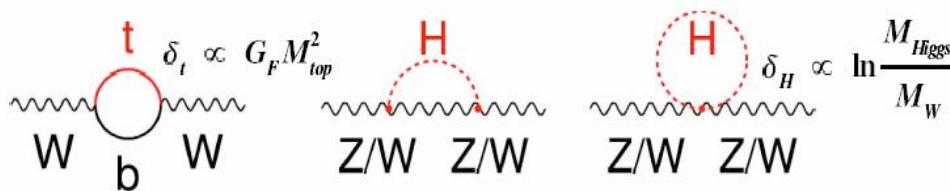


# Bright Future with Inverse Femtobarns!

CDF+D0 will achieve  $\pm 2.5 \text{ GeV}/c^2$  in 2006!  
Will reach  $\pm 1.5 \text{ GeV}/c$  with  $4 \text{ fb}^{-1}$  base!

Shown is only lepton+jets channel with  
 $W \rightarrow jj$  jet energy calibration

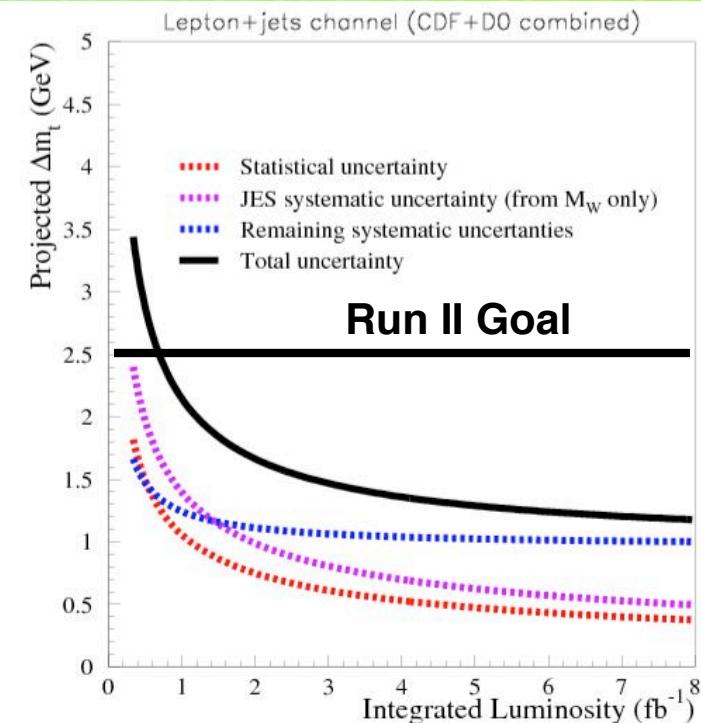
Conservative estimate of other  
systematics, will get smarter with more  
data!



Quantum loops make W mass  
sensitive to top and Higgs mass

Recent theoretical calculation of  
full two-loop electroweak  
corrections

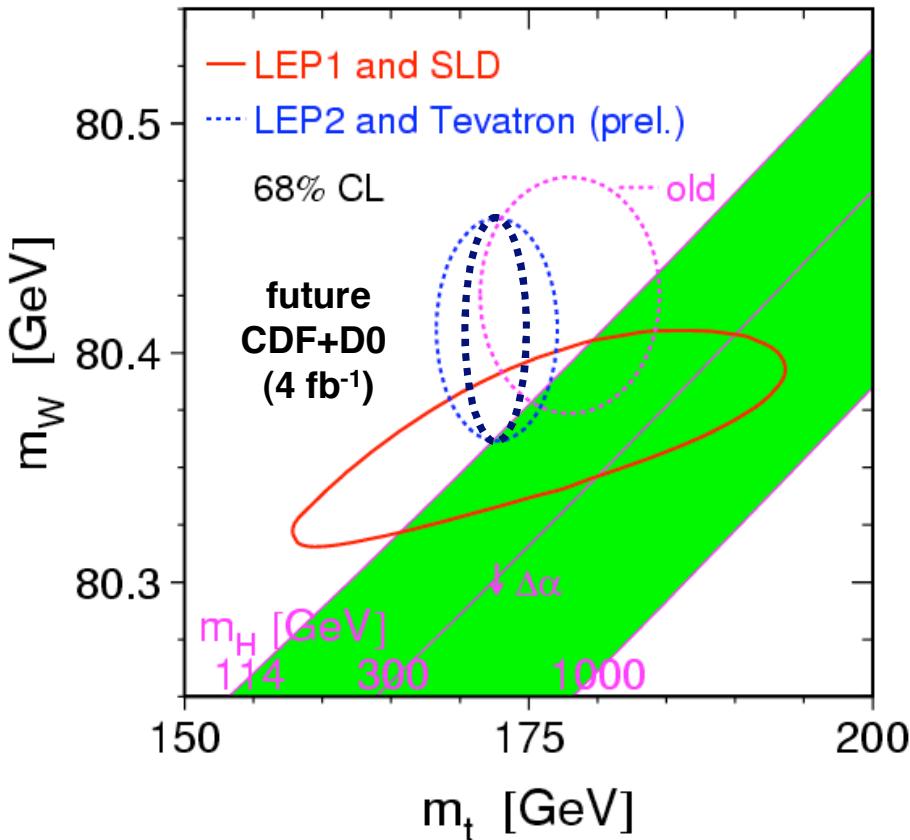
Precise prediction of W mass in  
standard model limited by  
uncertainty on experimental  
measurement of top mass



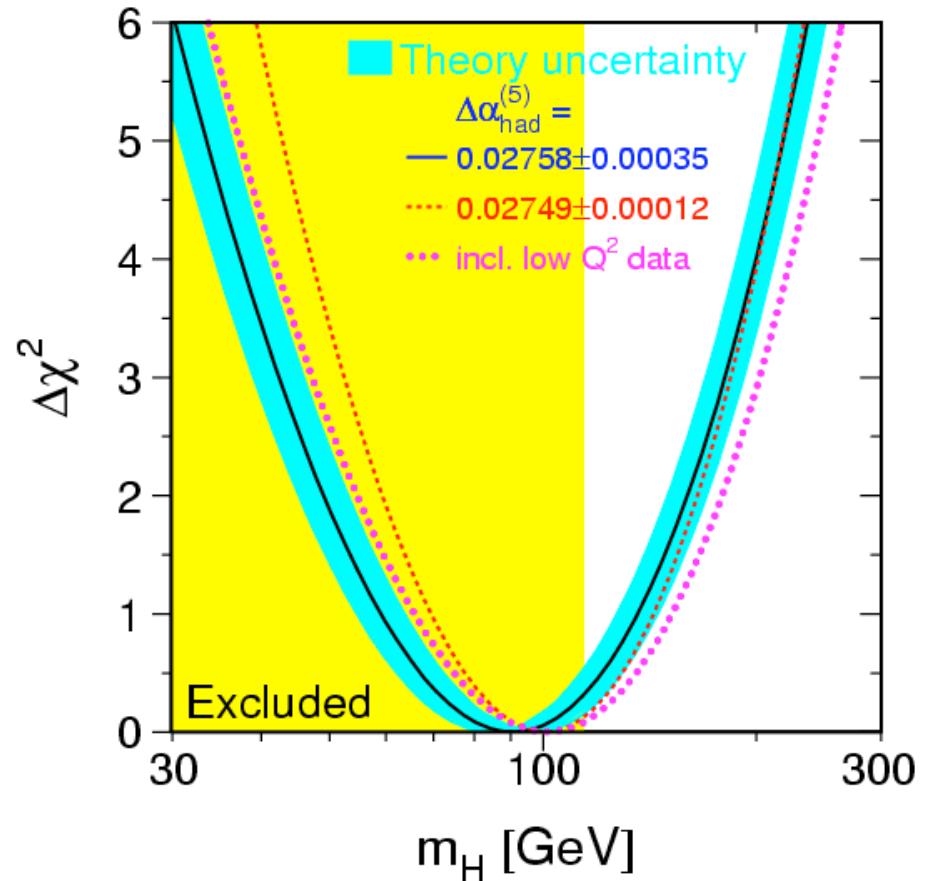
Adapted from A. Freitas <i>et al</i> hep-ph-0311148	Experiment $\delta M_{\text{top}}$ ( $\text{GeV}/c^2$ )	Prediction $\delta M_W$ ( $\text{MeV}/c^2$ )
CDF+D0 Run I	4.3	26
CDF+D0 2005	2.9	18
CDF+D0 $1 \text{ fb}^{-1}$	2.0	12
CDF+D0 $4 \text{ fb}^{-1}$	1.5	9
LHC	1.3	8

# Test of Standard Model

## Impact of CDF+D0 Top Quark Mass = $172.7 \pm 2.9$ GeV



Good agreement between  
direct measurements  
and  
indirect SM prediction



$= 91 \pm ^{45}_{32}$  GeV  
 $< 186$  GeV @ 95% C.L.

**$< 219$  GeV with LEP Excluded**

# Conclusions

**Observed top quark consistent  
with standard model  
so far**

**Achieved  
1.7% precision  
top quark mass measurement**

**Future is bright!  
Excellent performance of Tevatron & CDF & D0  
delivering high statistics samples of top quarks**

**Watch out for interesting results with 1 fb<sup>-1</sup>  
at Moriond 2006!**